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Comisión Nacional de Energía Atómica
Departamento de Metalurgia

PRIMERA CONFERENCIA DE EXPERTOS LATINOAMERICANOS

EN METALURGIA DE TRANSFORMACION

FIRST LATIN AMERICAN CONFERENCE ON PROCESS

METALLURGY AND METAL WORKING

Buenos Aires, 18 - 23 Agosto, 1964

VOLUMEN II

1966

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Esta Conferencia fué patrocinada por la Air Force Office
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B-1

INDICE - INDEX

VOLUMEN I

IV.   -"Plan de Actividades del Departamento de Metalurgia de la Comisión Nacional de Energía Atómica, Argentina"
-"Plan of Activities of the Department of Metallurgy of the CNEA"
        JORGE A. SABATO
        (Departamento de Metalurgia. CNEA, Argentina)

V.   -"Plan de Actividades del Servicio de Asistencia Técnica a la Industria Metalúrgica"
-"Plan of Activities of the Service of Technical Assistance to Industry (SATI)"
        OSCAR WORTMAN
        (Departamento de Metalurgia, CNEA, Argentina)

VI.   -"Breve Reseña de la Investigación Metalúrgica en Chile"
-"A Review of the Metallurgical Research Activities in Chile"
        DAVID FULLER
        (Universidad Católica de Chile)

VII.   -"Algunos Comentarios sobre la Metalurgia Física del Hierro y del Acero"
-"Some Remarks on the Physical Metallurgy of Iron and Steel"
        H. PAXTON
        (Carnegie Institute of Technology, USA)

VIII.   -"Nuevos Aceros Americanos Ultra Resistentes"
-"New American Ultrahigh-strength Steels"
        F. MORRAL
        (Batelle Memorial Institute, USA)

IX.   -"Racionalización en el empleo de aceros de construcción"
-"Rationalized Use of Constructional Steels"
        DIONISIO FARIAS
        (Universidad Católica de Córdoba, Argentina) -

X.   -"Materiales Metálicos Celulares"
-"Cellular Metallic Materials"
        S. LIPSON
        (Frankford Arsenal, USA)

XXVI. -"Propiedades de una Aleación de Cobre de Alta Resistencia al
Ablandamiento y Alta Conductividad"
-"Fabrication and Properties of a High Resistance to Softening and
High Conductivity Copper Alloy"
D. OBRUTSKY, M. SARRATE, O. WORTMAN
(Departamento de Metalurgia, CNEA, Argentina)

XXVII. -"Manufactura de Chapas No-Ferrosas"
-"Non Ferrous Metal Sheet Manufacturing"
F. MORRAL
(Battelle Memorial Institute, USA)

XXVIII. -"Influencias de las Investigaciones sobre Materiales en la Optimi-
zación de Diseño"
-"Design Optimization Through Materials Research"
M. STEINBERG
(Lockheed Missiles and Space Co., USA)

XXIX. -"Trabajado de Metales con Explosivos"
-"Explosive Working of Metals"
J. RINEHART
(Colorado School of Mines, USA)

XXX. -"Nuevos Procesos de Manufactura de Metales en los EE. UU. -
Posible Aplicación en Países Latinoamericanos"
-"New Metal Manufacturing Processes in the USA of Possible Ap-
plication in Latin American Countries"
F. MORRAL
(Battelle Memorial Institute, USA)

XXXI. -"Colada Contínua de Aluminio"
-"Continuous Casting of Aluminum"
J. CIARLO, R. MEILLAT
(C. A. M. E. A.. Argentina)

XXXII. -"Estudio de la Colaminación de metales"
-"Roll-bonding of Metals"
J. ALMAGRO, G. CUSMINSKY, C. A. MARTINEZ VIDAL
(Departamento de Metalurgia, CNEA, Argentina)

XXXIII. -"Influencia del Efecto de Tamaño y Entalladura en la Resistencia a
la Fatiga de Elementos Estructurales y de Máquinas"
-"The Effect of Size and Shape on the Fatigue Strength of Structural
and Machine Members"
R. KUGUEL
(Ins. Nacional de Tecnología Industrial, INTI, Argentina)

ALGUNS PROBLEMAS DE CORROSAO DE METAIS (*)

Stephan Wolynec (**)
Idel Metzger (***)

RESUMO -   No presente trabalho os autores fazem um apanhado
sobre alguns problemas de corrosao de metais que devido ao seu
alto gráu de destrutividade tem sido trazidos para estudo no Insti-
tuto de Pesquisas Tecnológicas. A descriçao de cada caso é prece
dida de um resumo teórico sobre o mecanismo particular da corro
sao que nele atua. Sao descritos os seguintes casos: corrosao por
correntes dispersas ("stray currents") de tubos de aço enterrados
de uma adutora de água; corrosao sob tensao ("stress corrosion")
de arames de aço empregados na protensao de concreto; corrosao
de contato ("crevice corrosion") de chapas de aço inoxidável; cor-
rosao intergranular devida a sensitizaçao (precipitaçao de carbone
tos intergranulares) de tubos de aço inoxidável.

I   INTRODUÇAO

Os prejuizos que a corrosao dos metais causa a indústria e a comunidade constituem uma parcela apreciável da sua receita. Ela diminui a eficiencia dos equipamentos, contamina produtos, destrói estruturas e causa acidentes.

A aplicaçao de processos científicos e tecnológicos pode reduzir de maneira efetiva os efeitos da corrosao. Em várias partes do mundo estuda-se, exaustivamente, o fenomeno e desenvolvem-se técnicas e produtos, sempre mais eficientes no sentido de minorar a sua açao.

No Brasil pouca atençao tem sido dispensada aos problemas de corrosao. O nosso "know how" sobre o assunto é ainda incipiente. O recente desenvolvimento tecnológico do país exige, no entanto, que se lhe de a devida importancia.

No decorrer dos últimos 20 anos, o Instituto de Pesquisas Tecnológicas de Sao Paulo teve oportunidade de, através da sua Secçao de Metalografia e, no último ano, através da Secçao de Físico-Química Metaldrgica, lidar com uma variedade apreciável de problemas de corrosao, o que lhe permitiu acumular certa experiencia no assunto. O presente trabalho visa difundir alguns dos problemas aparecidos nesse tempo e que apresentam interesse geral.

Dentre os problemas de corrosao, devemos distinguir os fenomenos, que sao corriqueiros, daqueles cujas consequencias inesperadas os fazem assumir importancia excepcional. Referimo-nos, no primeiro caso, aos problemas de corrosao de estruturas metálicas em meios perfeitamente conhecidos e cuja agressividade e também perfeitamente previsível. Neste caso, uma vez considerados os fatores economicos, procura-se utilizar os metais ou métodos mais apropriados para resistir a agressividade do meio. Desse modo, a corrosao fica sob controle, isto é, a açao destrutiva da corrosao é diminuida ao máximo, dentro dos limites viáveis e é computada no custo de utilizaçao, quando necessário.

No segundo caso, os problemas que surgem nao sao previstos e resultam de condiçoes que nao foram levadas em consideraçao quando do projeto da estrutura. Em virtude disso, nen sempre se faz a escolha apropiada dos metais ou métodos de proteçao contra a agressao do meio, resultando, em geral, um colapso desastroso. O desconhecimento de certas características físico-químicas do meio e a nao consideraçao de certas fatores mecanicos e de construçao como possíveis promotores da corrosao, levam a adoçao de projetos impróprios, com suas consequencias posteriores.

De um modo geral, os problemas trazidos a apreciaçao do Instituto de Pesquisas Tecnológicas enquadram-se nesse segundo caso. Trata-se, quase sem

pre, de corrosoes que, em face de seu desenvolvimento altamente danoso, causam graves transtornos aos interessados.

Os problemas que passamos a descrever referem-se a corrosao por correntes dispersas, corrosao em frestas, corrosao intergranular de aços inoxidáveis e corrosao sob tensao. A descriçao de cada problema é precedida de um resumo teórico sobre o mecanísmo particular de corrosao que nele atua.

II   CORROSAO DE METAIS POR CORRENTES DISPERSAS

II.1   Mecanísmo da corrosao

A corrosao por correntes dispersas ("stray-currents corrosion" ou "electrolysis") ocorre em estruturas metálicas enterradas ou submersas. Ela é devida a correntes causadas por uma diferença de potencial entre a estrutura em questao e partes de outras instalaçoes ou equipamentos próximos. Essa diferença de potencial é geralmente causada por um gerador, de corrente contínua ou, entao, uma outra estrutura que se encontra num potencial diferente.

Os danos que esse tipo de corrosao pode causar sao de apreciável monta, uma vez que há uma aceleraçã o e uma localizaçao preferencial do ataque. A seguir, damos alguns exemplos de casos em que a corrosao por correntes dispersas pode ocorrer:

-       corrosao de oleodutos ou aquedutos, enterrados próximos de estradas de ferro eletrificadas ou linhas de bondes;

-       corrosao de cascos de navios em virtude das operaçoes de solda elétrica, quando acostados em estaleiros para construçao ou reparos;

-       corrosao de estruturas enterradas, quando próximas de outras protegidas catódicamente;

-       etc.

O aparecimento de correntes dispersas num determinado meio eletrolítico é devido a uma deficiencia, ou eventualmente ausencia, de isolamento de alguma porçao de um circuito que passa por esse meio e que encontra-se num potencial diferente do potencial do meio. Como a condutividade média da maioria dos me-

tais é muito maior do que condutividade média dos diferentes eletrólitos, princi-
palmente se considerarmos como tais o solo ou a água do mar, as estruturas en-
terradas ou submersas atuam como condutores de baixa resistencia e, em conse-
quencia, passam a conduzir a maior parte da corrente causada pela diferença de
potencial mencionada.

Existem dois mecanismos pelos quais as correntes dispersas podem pro-
mover corrosao numa estrutura metálica (1). No primeiro mecanismo, esquemati
zado na Fig. 1, uma parte da corrente dispersa que passa pela estrutura é, em
virtude do gradiente de potencial existente, desviada pelo eletrólito. No segundo
mecanismo, esquematizado na Fig. 2, há uma inversao de papéis, cabendo a es-
trutura metálica desviar parte da corrente dispersa que circula pelo eletrólito.
Tanto o primeiro como o segundo mecanismos dao origem as células de corrosao,
responsáveis pela entrada, na regiao anódica, de cations metálicos em solução no
eletrólito. Essas células de corrosao dao origem as chamadas "correntes de cor-
rosao" que podem ser encaradas como fluxos de cargas positivas. Esses fluxos
nao sao necessáriamente acompanhados de movimento de cations, mas antes pela
transferencia de carga de um cátion a outro. O sentido de uma corrente de corro
sao coincide com o sentido convencional de uma corrente elétrica, ou seja, é con
trário ao sentido do fluxo das cargas negativas.

Em cada um dos mecanismos, tanto a regiao anódica como regiao catódi-
ca, sao sujeitas a polarizaçao devido a corrente que flui pelo circuito de corrosao
Esta polarizaçao é uma funçao da corrente do circuito. Assim, sendo V_c^o e V_a^o os
potenciais do catodo e do anodo, respectivamente, em circuito aberto; os corres-
pondentes potenciais V_c e V_a em circuito fechado serao (2):

$$V_c = V_c^o - f_c (i) \qquad (1)$$

$$V_a = V_a^o + f_a (i) \qquad (2)$$

onde

$f_c(i)$ = funçao de polarizaçao do catodo,
$f_a(i)$ = funçao de polarizaçao do anodo e
i   = corrente de corrosao

Tendo em vista a segunda lei de Kirchhoff, pode-se escrever:

$$V_c - V_a = Ri \qquad (3)$$

onde

R   = resistencia total do circuito de corrosao.

Substituindo (1) e (2) em (3), resulta:

$$(V_c^0 - V_a^0) - f_c(i) + f_a(i) = Ri$$

Como $V_c^0 - V_a^0 = V_d$ = diferença de potencial induzida por correntes disper
sas e fazendo-se $f_c(i) + f_a(i) = f(i)$, resulta:

$$i = \frac{V_d - f(i)}{R} \qquad (4)$$

II.2 Meios de prevenção

Tendo em vista que a intensidade da corrosao é uma função direta da cor-
rente i, todo processo que vise diminuf-la deve reduzir o valor de i sem aumentar
a densidade da corrente anódica. Deste modo, considerando-se a relaçao (4), a
corrosao porcorrentes dispersas pode ser debelada por (1):

a - diminuiçao ou eliminaçao de V_d;

b - aumento de f (i);

c - aumento de R.

a   Diminuiçao ou eliminaçao de V_d:

Esta diminuiçao ou eliminaçao pode ser conseguida de dois modos:

1º   por eliminaçao das correntes dispersas, isolando-se convenientemen-
te todo o circuito responsável pelo seu aparecimento no eletró
lito;

2º   Levando a estrutura a um potencial mais negativo, ou seja, tornan
do-a catódica com relaçao ao eletrólito. Conseguese isto por vários
processos, entre os quais, a proteçao catódica e a ligaçao da estru
tura ao poio negativo da fonte geradora das correntes lispersas
constituindo os meios mais práticos.

Aumento de f(i):

O aumento da polarizaçao f(j) se consegue revestindo as regioes ca
tódicas da estrutura com camadas protetoras apropriadas (em geral, asfal
to betuminoso). Com isto promove-se, em virtude dos furos no revestimen
to, um aumento na densidade de corrente catódica e, em consequencia, da
polarizaçao. Este processo, em geral, é de difícil aplicaçao pois a locali-
zaçao das áreas catódicas nao é simples.

c   **Aumento de Ri:**

O aumento da resistencia do circuito pode ser conseguido aumentan
do-se a resistencia do eletrólito que circunda a estrutura. No caso de es-
truturas enterradas no solo consegue-se isto substituindo o solo, que cir-
cunda a estrutura, por um material de elevada resistividade elétrica como,
por exemplo, areia limpa. Um outro processo de aumentar R consistiria
em se aumentar a resistencia da estrutura, inserindo juntas isolantes entre
várias porçoes da mesma. No entanto, este processo pode, as vezes, criar
problemas de corrosao por correntes dispersas nas partes internas de es-
truturas que contem eletrólitos.

A adoçao, de um ou outro processo de eliminaçao ou diminuiçao de corro-
sao por correntes dispersas é determinada por fatores economicos peculiares a
cada caso.

II. 3   Corrosao de tubos de uma linha adutora de água

a)   Generalidades

O caso que passamos a descrever constitui um exemplo típico da
corrosao de metais por correntes dispersas. Trata-se da corrosao ocor-
rida com os tubos de aço da linha adutora de água de um município do
Estado de Sao Paulo (3).

A linha adutora estende-se por cerca de 14 km, entre o reservató
rio e a caixa d'água da cidade. Ela é constituida por tubos de aço de 500
mm de diametro, ligados por solda, e apresenta dois trechos distintos.

O primeiro trecho, que se estende desde o reservatório até, aproximadamente, metade do percurso da adutora, é o mais antigo e é constituido por tubos soldados lateralmente. O segundo trecho, que corresponde ao restante da adutora, é o mais recente e é constituido por tubos soldados em hélice.

Toda a linha adutora é subterranea, com exceçao das regioes em que ela atravessa lagoas ou riachos e de em que ela passa sobre uma estrada de ferro. Nessas regioes ela é aérea.

Os tubos da adutora sao todos revestidos externamente por uma camada de "primer" e uma outra de asfalto, sendo que, nos tubos do trecho mais novo, esse asfalto apresenta-se misturado com la de vidro. A espessura do revestimento, no trecho mais velho, varia entre 2,5 e 3,0 mm e no mais novo entre 3,5 e 4,0 mm.

Em dois pontos de seu percurso a linha adutora cruza com a estrada de ferro. Um desses pontos já foi mencionado anteriormente e o outro situa-se numa regiao na qual a adutora passa por baixo dos trilhos.

A disposiçao da estrada de ferro, com relaçao a linha adutora, é mostrada na Fig. 3. Observa-se que ela se matém razoavelmente paralela a linha adutora num percurso de, aproximadamente, 2 km, variando a distancia entre ambos de 125 a 325 m.

A estrada de ferro é de uma única via e emprega sistema de traçao elétrico por corrente contínua. A tensao na linha é de 600 volts e os trilhos estao ligados ao terminal negativo dos geradores. No trecho indicado na Fig. 3, a estrada de ferro é alimentada por dois geradores. Um desses geradores (Gerador 1) está instalado perto da cidade e a sua açao estende-se para além do cruzamento com a linha adutora.

O trecho restante da linha é alimentado por um outro gerador (Gerador 2) instalado no outro extremo do estrada de ferro.

b)   Observaçao da corrosao

A corrosao dos tubos da adutora foi notada ao longo de todo o seu percurso. No entanto, manifestou-se de modo mais grave em duas regioes, cada uma próxima de uma lagoa e nao muito afastada da estrada de ferro. A primeira dessas regioes localiza-se no trecho mais antigo da adutora, próximo ao seu cruzamento com a estrada de ferro na qual a adutora passa

sob os trilhos. Um esquema do perfil dessa regiao está indicado na Fig.4. A segunda regiao, consideravelmente atacada, encontra-se no trecho novo da adutora e corresponde a porçao que mais se aproxima da estrada de ferro, antes do ponto em que as duas se separam (ver regiao assinalada na Fig.3).

Em ambas as regioes a corrosao promoveu nos tubos mais de 100 furos, resultando, em consequencia, fortes vazamentos. Este fato provocou uma forte erosao no terreno, expondo uma boa parte da tubulaçao e chegando, em certos lugares, a criar problemas de estabilidade mecânica. A Fig.5 mostra o alcance da erosao provocada pelos vazamentos num trecho próximo do cruzamento com a estrada de ferro. Como soluçao provisória, os furos resultantes da corrosao foram tapados com pinos de madeira, como pode ser observado na Fig. 6.

Em muitos dos pontos, onde as tubulaçoes foram expostas, observou-se ausencia do revestimento externo. Isto foi motivado, provávelmente, pelos danos causados por correntes, talhas ou outros instrumentos empregados durante a sua colocaçao, ou entao, pela açao do solo e das raízes. Além disso, a remoçao de alguns pedaços do revestimento do tubo revelou tratar-se de um produto bastante quebradiço e, em certos pontos, esponjoso.

A corrosao, no entanto, manifestou-se de preferencia em pontos aparentemente revestidos. O início da corrosao deu-se sob o revestimento e a sua continuaçao era caracterizada pela formaçao de uma protuberancia do tipo observado na Fig. 7; a quebra do revestimento da protuberancia revelou um material amarelado que era o produto da corrosao do tubo e também do próprio revestimento. A remoçao deste produto mostrou-se que a corrosao do tubo de aço é do tipo alveolar (pitting corrosion) conforme pode ser observado na Fig.8 e na Fig.9; a Fig. 8 apresenta a mesma regiao da Fig.7, porém, após a remoçao de uma das protuberancias e do respectivo produto de corrosao. O desenvolvimento da corrosao dos tubos está esquematizado na Fig. 10.

A disposiçao dos furos na tubulaçao era, em geral, ao acaso, porém observou-se uma certa predominancia deles na parte inferior e lateral. As regioes soldades, de modo geral, nao foram atacadas a nao ser em alguns pontos.

c) Ensaios realizados

A fim de verificar-se a agressividade do solo, foi retirada uma amostra do mesmo nas regioes fortemente corroídas e executou-se a determinaçã do potencial de oxidaçao-red. ;ao. Essa determinaçao foi feita com refe, ncia ao eletrodo de calomelano e apresentou como resultado o valor de 0,268 volts. Starkey e Wight (4) determinaram uma correlaçao entre o potencial de oxidaçao-reduçao de um solo e a correspondente seve ridade de corrosao, estabelecendo o seguinte critério:

Faixa do potencial de oxidaçao-reduçao do solo	Grau de corrosividade
Abaixo de 100 mv	Severo
100 a 200 mv	Moderado
200 a 400 mv	Leve
Acima de 400 mv	Nao corrosivo

Desse modo, o valor encontrado classifica o solo da regiao como sendo levemente corrosivo.

Para verificar o comportamento eletrolítico dos tubos enterrados, determinou-se, em vários pontos da linha adutora no trecho próximo do cruzamento com a estrada de ferro, a diferença de potencial entre o tubo e o solo. Essas determinações foram feitas com auxílio de uma meia célu la de (cobre-sulfato de cobre) e de um voltímetro, conforme esquema re presentado na Fig.11. Os resultados obtidos estao na Tabela I e correspon dem aos pontos indicados na Fig. 4.

TABELA I

Ponto de ensaio	Potencial tubo-solo (volts)	
	Meia célula sobre o tubo	Meia célula a 7 m do tubo
1	- 0,483	-
2	- 0,775	- 0,580
3	- 0,685	Variável com o tempo en- tre -0,5 e + 2,5
4	Variável com o tempo en- tre -0,5 e +3,5	

Os resultados nao-variáveis da Tabela I foram obtidos quando o trem nao se achava na linha ou entao estava afastado para o lado da cida- de. Já os resultados variáveis com o tempo foram determinados quando o trem percorria os trechos próximos da linha adutora.

A méia célula empregada no ensaio foi montada no Instituto de Pes quisas Tecnológicas e está indicada na Fig.12. A Fig.13 mostra os seus detalhes construtivos.

A variaçao com o tempo do potencial tubo-solo provou a existencia de correntes dispersas na regiao testada (5). Por outro lado do potencial tubo-solo se tornar menos negativo quando a determinaçao se fez com a célula afastada do tubo, provou que essa regiao era anódica (6).

d) Causas da corrosao

Em face das observaçoes e dos ensaios realizados concluiu-se que os principais causadores da corrosao dos tubos da adutora, nas duas re- gioes mais fortemente atingidas, foram as correntes dispersas. Estas cor rentes foram devidas aos geradores da estrada de ferro, pois uma parte da corrente que passava pelos trilhos era desviada pelo solo. Como a conduti. vidade da maioria dos metais é cerca de um bilhao de vezes maior do que a condutividade média dos solos (7), os tubos de aço enterrados atuaram como comdutores de baixa resistencia e conduziram a maior parte desviada da corrente dos trilhos. Nestas condiçoes criaram-se regioes catódicas e anó dicas ao longo de linha adutora. A Fig. 14 ilustra esquematicamente o fe- nómeno.

As correntes dispersas nao podem ser consideradas como as únicas responsáveis pela corrosao, no entanto, elas aceleraram-na consideravel- mente, principalmente no que se refere a formaçao de furos. De fato como se mencionou antes, os furos ocorriam de preferencia em regioes aparente mente revestidas pelo asfalto. Isso foi devido, na realidade a existencia de pequenas trincas no asfalto que se encarregaram de colocar o aço do tubo em contato com o eletrólito do solo. Essas 5 trincas funcionaram pois, como verdadeiros condutores elétricos, e como a corrente que passou pe- los tubos foi aumentada pelas correntes dispersas, a densidade de corren te nas regioes em contato com essas trincas passou a ser bastante levada, em virtude da pequena área. Desse modo, a corrosao se tornou locali zada e rápida.

Apesar do ensaio realizado com uma amostra de solo ter revelado

tratar-se de um solo apenas ligeiramente corrosivo, a sua açao, aliada
com a dos demais fatores, foi de considerável monta. Deve-se, princi-
palmente, levar em conta que as regioes mais atingidas pela corrosao lo
calizam-se próxima de lagoas, e que é justificável, pois nestes locais. a
resistividade do solo é diminuida pela umidade resultante dessa proximi-
dade. Essa baixa resistividade facilitou a circulaçao de correntes disper
sas pelo solo e, em consequencia, aumentou a sua agressividade.

Cumpre notar que o ensaio realizado com o solo tem significaçao
restrita, uma vez que nao computa a influencia da umidade e da aeraçao.

O revestimento asfáltico dos tubos da linha adutora, conforme foi
possível observar nos trechos descobertos pela erosao, perdeu a sua con
tinuidade, isto é, tornou-se trincado e deformado. Essa perda de conti-
nuidade foi mais acentuada no trecho mais velho da linha adutora e foi de
vida, principalmente, a ausencia de la de vidro, que normalmente costu-
ma-se adicionar ao asfalto, antes de sua aplicaçao sobre os tubos, a fim
de aumentar a sua resistencia as distorçoes e a formaçao de trincas.
Além disso, a camada de asfalto nesse trecho nao foi suficientemente es
pessa, o que diminuiu a sua resistencia a absorçao de água (8). A água
absorvida pelo revestimento tornou-o esponjoso e quebradiço, e fez com
que ele perdesse as suas qualidades protetoras, favorecendo na realidade
ainda mais o aparecimento da corrosao alveolar.

e) Medidas sugeridas para eliminar a corrosao

Tendo em vista as causas que promoveram a corrosao dos tubos
da linha adutora, sugeriou-se uma das seguintes medidas para eliminar
ou, eventualmente, diminuir a corrosao por correntes dispersas:

1. S ibstituir o solo que circunda os tubos por um material de
    e evada resistividade elétrica como, por exemplo, areia
limpa.

2. Inserir juntas isolantes entre várias porçoes da linha adu-
    tora. Este processo apenas reduziria a corrosao por cor-
rentes dispersas, porém, nao a eliminaria.

3. Aplicar proteçao catódica. Neste caso poder-se-ia promo
    ver proteçao total da linha desde que se criasse, nos tubos,
um potencial mais negativo do que -0,85 volts em relaçao a me: '
célula de (cobre)-(sulfato de cobre)(1). Isso pode ser conseguic

através de anodos de sacrifício ou, entao, de geradores de corren
te contínua, cuja instalaçao e dimensionamento exigiram um levan
tamento completo da resistividade do solo e do potencial tubo-solo
ao longo de toda a linha adutóra.

4.　　　Ligar os tubos da linha adutora aos trilhos da estrada de
　　　　ferro. Este método que de todos é o mais acessível, consis
te na ligaçao dos tubos da linha adutora aos trilhos da estrada de
ferro, ou entao, se possível, ao polo negativo do Gerador, por
meio de um condutor bem isolado, e através de um transformador-
retificador, conforme esquema indicado na Fig.15. O sistema deve
ser dimensionado para suportar correntes de até 100 amperes (9).
Os pontos sugeridos para a ligaçao entre a linha adutora e a estrada
de ferro estao indicados na Fig.3 e sao os mais convenientes, pois
correspondem aos trechos mais anódicos da linha.

III　　CORROSAO EM FRESTAS

III.1　Mecanismo da corrosao

A corrosao em frestas ("crevice corrosion") caracteriza-se por um ata-
que altamente localizado e ocorre nas frestas que resultam do contato de duas pe
ças de materiais diferentes ou de mesmo material. Este tipo de corrosao somen
te ocorre em presença de um eletrólito que consegue penetrar nas frestas. Como
nessas frestas a aeraçao é pequena, resulta, em consequencia, uma diferente
concentraçao de oxigenio no eletrólito que se encontra dentro das frestas e no ele
trólito que se encontra em contato com o material na parte externa. A Fig.16 es-
quematiza esse fenomeno.

A diferença de concentraçao em oxigenio desenvolve, na superfície da
maioria dos metais e suas ligas, áreas catódicas e anódicas correspondentes,
respectivamente, as regioes de alta e baixa concentraçao em oxigenio. Criam-se,
assim, as chamadas "células de concentraçao de oxigenio" (10) que promovem
uma corrosao acentuada de um metal que esteja em contato com a fresta.

A corrosao em frestas ocorre com uma série de metais e ligas em uma
grande variedade de meios corrosivos. No entanto, os metais e ligas que apre-
sentam tendencia a passivaçao, ou seja, formaçao de uma película fina e aderen
te de óxido na superfície, sao particularmente sensíveis a esse tipo de ataque.
É o caso, por exemplo, do alumínio, chumbo e aço inoxidável, entre outros. Nes

tes metais, o empobrecimento de oxigenio destrói o seu "film" protetor, tornando-os quimicamente mais ativos. Assim, quando este empobrecimento é confinado ape nas a uma porçao da sua superfície, resulta uma diferença de potencial entre a porçao que se tornou ativa, e o restante da superfície, que continua passiva, dando origem a chamada "célula ativa-passiva". (11). A açao dessa célula simultaneamente com a de concentraçao de oxigenio reforça a intensidade de corrosao.

A corrosao em frestas nem sempre ocorre na regiao de contato. Há casos em que ela se dá na regiao imediatamente próxima ao contato dos materiais, porém fora das frestas. É o que costuma ocorrer, as vezes, com o cobre e as ligas de alto cobre (11). Neste caso, ocorre uma acumulaçao de íons de cobre dentro da fresta e resulta uma célula de concentraçao de cobre, cuja açao é contrária a de uma célula de concentraçao de oxigenio. Esta célula está esquematizada na Fig.17. Quando a concentraçao dos ions de cobre atinge um determinado nível, ela se tor na mais ativa do que a de concentraçao de oxigenio e promove a corrosao na regiao citada.

III.2 Fatores dos quais depende a corrosao em frestas

A corrosao em frestas, de um metal ou liga, depende de uma série de fa tores, entre os quais podem ser citados os seguintes:

a natureza do material em contato;
b natureza do eletrólito;
c pH do eletrólito;
d espessura da fresta;
e tensao superficial do eletrólito;
f vulnerabilidade do metal ou liga em perder a
   passividade;
g extensao da área externa as frestas.

a Natureza do material em contato

Certos materiais quando em contato com um metal ou liga favorecem mais a sua corrosao do que outros. Assim, sao particularmente pro pícios a corrosao em frestas os seguintes materiais (11): madeira, plásti cos, vidro, tecidos, borracha, porcelana, mica, cera, asbestos, organis mos marinhos, etc. Materiais que contem enxofre sao, de um modo geral mais danosos do que aqueles que nao o contém. Por exemplo, uma borra cha que contém enxofre causa maior corrosao em frestas do que uma livre de enxofre. Trata-se de uma açao suplementar a das células pelo enrique-

cimento do eletrólito em compostos de enxofre.

b   Natureza do eletrólito

Os tipos de eletrólitos que promovem a corrosao em frestas sao as soluçoes de sais e de certos ácidos redutores. (11) Entre as soluçoes de sais merece destaque a de cloreto de sódio, nao tanto pela sua agressivida de, como pelo fato de ser uma das mais comuns causadoras desse tipo de corrosao. De um modo geral, soluçoes que apresentam ions halogenios sao apropriadas ao desenvolvimento da corrosao em frestas (15). Em certos casos peculiares esta corrosao pode ocorrer também em presença de solu çoes de ácidos oxidantes, como por exemplo, ácido nítrico. Contudo, o mecanismo de perda de passividade do metal é, neste caso, distinto.

c   pH do eletrólito

A influencia do pH do eletrólito sobre a corrosao em frestas depen de da natureza do metal ou liga. De um modo geral, metais e ligas ferro sas sao mais susceptíveis a corrosao em frestas quando o eletrólito é neu tro ou ácido (11). Alumínio e suas ligas sao menos susceptíveis a essa corrosao apenas em meio neutro.

d   Espessura da fresta

A espessura de uma fresta formada pelo metal e o material em con tato varia de uma caso a outro, dependendo do estado de acabamento da su perfície de cada um deles e do aperto a que ficam sujeitos. Em geral ela é da ordem de centésimos de milímetro ou menos (11). Nao é possível estabele cer de um modo completo qual a espessura mais favorável para a corrosao em frestas, uma vez que ela depende de todos os demais fatores. No entan to, uma vez fixados esses fatores, existirá uma espessura ótima para o de senvolvimento da corrosao em frestas, na qual é possível o acesso do ele- trólito a fresta. Concomitantemente, essa espessura ótima vai permitir uma grande diferença de concentraçao de oxigenio.

e   Tensao superficial do eletrólito

A influencia da tensao superficial do eletrólito, sobre a corrosao em fresias, está intimamente ligada a espessura das frestas, pois é ela quem estabelece a "molhabilidade" das frestas pelo eletrólito, e por con seguinte, determina as regioes que serao atacadas.

f   Vulnerabilidade do metal ou liga em perder a passividade

Trata-se da maior cu menor facilidade com que um metal ou liga dá origem a uma "célula ativa-passiva", uma vez que a destruiçao do filme protetor, devido ao empobrecimento en oxigenio, nao se dá com a mes ma facilidade em todos eles. Assim, por exemplo, o aço inoxidável AISI 304, é mais vulnerável a perda de passivaçao do que o aço inoxidável AISI 316, pois neste último, o molibdenio promove a formaçao de um "film" protetor mais estável de que no primeiro. Por esse motivo o aço AISI 316 resiste melhor a corrosao em frestas está diretamente ligada a extensao da área de metal que está livremente exposta, isto é, que nao está em con tato com o outro material. Quando esta área tende a zero, a corrosao dentro das frestas também tende a zero (12:

III. 3   Corrosao em frestas de chapas de aço inoxidável

a)   Generalidades

Como já se mencionou anteriormente, os aços inoxidáveis apresen tam-se particularmente sensíveis a corrosao em frestas em virtude da sua vulnerabilidade em perder a passividade quando ocorre uma diferença de concentraçao em oxigenio. O caso que passamos a descrever ilustra bem o fenomeno. Trata-se da corrosao em frestas de placas de aço inoxi dável empregadas numa máquina de pasteurizaçao de leite (13).

As placas em questao foram fabricadas a partir de chapas de aço inoxidável AISI 316 e apresentam o aspecto indicado no Fig.18. Na máqui na de pasteurizaçao de leite, as placas sao mantidas em posiçao vertical, cada uma apertada contra a outra através de vedaçoes de borracha. Conforme pode ser observado na Fig.18, essas vedaçoes ficam coladas as pla

cas dentro de canaletas periféricas apropriadas. Cada placa apresenta uma das faces em contato com a salmoura, de pH entre 8 e 9 e a temperatura abaixo de 0º C. A salmoura é alimentada através de um dos furos existentes nos cantos das placas. A outra face é mantida em contato com o leite, alimentado por um outro furo. A saída, tanto da salmoura como do leite, se dá pelos furos existentes no outro extremo da placa.

Após um certo período de uso, algumas placas foram, em virtude da sua corrosao, substituidas por novas, de fabricaçao mais recente. Contudo, constatou-se que essas placas novas nao estavam apresentando a mesma resistencia a corrosao que as antigas. Na Fig.18, a plaça antiga e a placa B uma nova.

A limpeza das placas, antes da colocaçao das novas, era feita semanalmente. Porém, como as placas novas começaram a apresentar maior corrosao do que as antigas a limpeza passou a ser realizada diariamente.

b)   Observaçao da corrosao

A corrosao foi observada apenas dentro das canaletas que estavam em contato com as borrachas de vedaçao e no lado que estava banhado pela salmoura. O tipo de ataque foi alveolar ("pitting corrosion"), conforme pode ser observado na Fig.19. A Fig.20 mostra uma secçao diametral de um desses alvéolos.

c)   Ensaios realizados

A fim de identificar os materiais empregados na fabricaçao das placas foram executados o exame metalográfico e a análise química. O exame metalográfico confirmou que tanto o aço da P¹ ₍ ₁ A como da Placa B apresentavam estrutura austenítica. A analise qu⁺ ₁ ₊ ₊a de₊ os seguintes resultados:

	Placa A	Placa B
C	0,10 %	0,10 %
Si	0,61 %	0,52 %
Mn	1,40 %	0,51 %
P	0,037%	0,031%
S	traços	traços
Cr	17,4 %	18,3 %
Ni	8,11 %	6,18 %
Mo	2,10 %	2,10 %

A composiçao nominal de um aço inoxidável AISI 316 é a seguinte:

C, max	0,08%
Mn, max	2,00%
Si, max	1,00%
Cr	16,00 a 18,00%
Ni	10,00 a 14,00%
Mo	2,00 a 3,00%

Verifica-se pois que os aços das duas placas nao atenderam as especificaçoes acima no que concerne ao carbono e níquel, principalmente este último, que na Placa B apresentou um valor bastante baixo.

d)   Tipo e causas da corrosao

Pelo fato da corrosao observada ter sido alveolar e tendo em vista que a mesma se manifestou em presença de um eletrólito (salmoura) na regiao de contato entre o aço e a borracha de vedaçao, conclui-se que trata-se de um caso de corrosao em frestas.

A explicaçao para a menor resistencia a corrosao em frestas da Placa B, quando comparada com a da Placa A, reside provavelmente no seu menor teor en níquel. É sabido que a resistencia dos aços inoxidávei: a corrosao normal, por soluçoes neutras de cloretos, é uma funçao dire.: do seu teor em níquel (14) conforme está ilustrado na Fig. 21. Esta resistencia pode ser extendida a corrosao em frestas, pois acreditamos que a oposiçao a perda de passivaçao varie no mesmo sentido.

Um fato que de. 2 ser levado em consideraçao, e que, provavelmente, acelerou a corrosao em frestas é o da medida que se adotou de executar-se a limpeza diariamente. Enquanto as pl. :as ficavam apertadas uma

contra a outra, a salmoura tinha pequeno acesso as frestas. Porém, quan do se desapertava as placas, as frestas se abriam e a salmoura adquiria maior facilidade de acesso e, como as vedaçoes sao coladas as placas, nao se consegueria eliminá-la completamente durante a limpeza. Desse modo, o aumento das operaçoes de desmontagem da sistema de placas au mentou o tempo de permanencia, das regioes cobertas pela borracha, em contato com a salmoura, resultando, em consequencia, uma maior corro sao.

e)   Medidas sugeridas para debelar a corrosao

A fim de debelar a corrosao em frestas das placas, sugeriram-se as seguintes medidas:

1.   Selagem com petrolatos. A aplicaçao de petrolatos (vaseli-
        nas) entre a placa e a vedaçao de borracha permite manter afastado o eletrólito da regiao susceptível a corrosao. Poderse-ia empregar outros produtos porém os petrolatos sao os mais eficien tes (11).

2.   Proteçao catódica (15.). Consistiria em se dispor alguns
        anodos de sacrifício, como por exemplo, de magnésio ou de zinco, ao longo do eixo dos furos de alimentaçao e saída da salmou ra. Esses anodos devem ficar convenientemente isolados das pla-cas na parte banhada pela salmoura, seído que a ligaçao anodo-pla ca deve ser feita externamente (16).

3.   Emprego de inibidores. Alguns compostos adicionados ao
        eletrólito parecem inibir a corrosao em frestas sendo, no entanto, discutível o seu mérito. Entre eles destacam-se: soda cáustica, carbonato de sódio, sulfato de sódio, sulfato de manganes, bicarbonato de potássio e nitrato de potássio (17).

IV   CORROSAO INTERGRANULAR DE AÇOS INOXIDÁVEIS AUSTENÍTICOS

IV.1   Introduçao

Certos aços inoxidáveis austeníticos ficam, sob certas condiçoes, suscep

tíveis a forte corrosao intergranular, mesmo quando o meio é relativamente pou-
co agressivo. Esse comportamento anormal ocorre quando os aços, após terem
sido solubilizados sao aquecidos, durante um certo tempo, dentro de uma determi
nada faixa de temperatura.

A susceptibilidade a corrosao intergranular pode ocorrer sob diferentes
circunstancias. Assim, por exemplo, durante uma operaçao de solda de um aço
austenítico inoxidável podem surgir áreas que, durante a operaçao e o resfriamen
to, permanecem tempo suficiente dentro da faixa crítica de temperaturas, para
promover a sua modificaçao de comportamento ante a corrosau. Do mesmo modo,
peças desses aços, empregadas em operaçoes sujeitas a temperaturas que caem
dentro da faixa crítica, sofrem o mesmo fenomeno.

Essa mudança de comportamento de um aço inoxidável austenítico, ante a
corrosao, é devida a precipitaçao de certos constituintes nos contornos dos graos
e que ocorre quando o metal é aquecido de modo mencionado. Trata-se da chama-
da sensitizaçao (18).

Os constituintes que precipitam nos contornos dos graos sao carbonatos
complexos de cromo e ferro. A corrosao intergranular nao se dá, no entanto, ao
longo desses constituintes, e sim ao longo das regioes compreendidas entre o cor
po dos graos e os constituintes precipitados.

Várias teorias foram propostas para explicar o mecanismo da corrosao in
tergranular dos aços inoxidáveis austeníticos. A ma.s difundida é a que admite que
a diminuiçao da resistencia a corrosao é devida ao empobrecimento em cromo das
áreas próximas dos contornos dos graos. Este empobrecimento é causado pela pre
cipitaçao dos carbonetos que removem quantidades apreciáveis de cromo dessas
regioes, uma vez que se constatou que a relaçao cromo/carbono nos carbonetos é,
aproximadamente, igual a 9. A Fig. 22 esquematiza a variaçao do teor de cromo
ao longo dos graos e seus contornos. Segundo a teoria em questao, as áreas empo
brecidas em cromo perderiam a sua tendencia a passivaçao e, em consequencia,
ficariam susceptíveis a corrosao. Essa teoria, no entanto, nao se aplica aos aços
austeníticos de elevado cromo e níquel (por exemplo, 25% Cr e 20% Ni), pois o
empobrecimento das áreas vizinhas aos carbonetos nao é suficiente para faze-las
perder a sua passivaçao. Por outro lado, ela tambén nao considera a influencia
do níquel que, como se verifica praticamente, aumenta a tendencia a corrosao in
tergranular (18).

Uma outra teoria aceita a mecanismo do empobrecimento, porém nao con
sidera a perda de passivaçao como a responsável pela corrosao, e sim a diferen-
ça de potencial que resulta da variaçao da concentraçao do cromo ao longo do grao. (19)
Segundo esta teoria, como o potencial eletroquímico de uma soluçao sólida de cro
mo em ferro varia diretamente com o teor de cromo, o núcleo de um grao ficaria

num potencial mais elevado do que a área empobrecida próxima do contorno do grao. Além disso, o próprio carboneto do contorno do grao também apresentar-se-ia potencial eletroquímico mais elevado do que o dessa área. Como consequencia, a área empobrecida em cromo ficaria anódica em relaçao aos demais constituintes e portanto, quando em presença de um agente corrosivo, seria a primeira a sofrer ataque químico.

Outras teorias foram propostas para explicar o fenomeno (20). Contudo, ater-nos-emos as acima citadas, pois um alongamento neste assunto fugiria aos propósitos do presente trabalho.

IV.2   Fatores que determinam a tendencia a corrosao intergranular.

A susceptibilidade dos aços inoxidáveis austeníticos a corrosao intergranular depende da sua tendencia a sensitizaçao e esta, por sua vez, depende de uma série de fatores, entre os quais podem ser citados, os seguintes:

1.   tempo de permanencia dentro da faixa crítica de temperaturas;

2.   teor de carbono;

3.   tamanho dos graos;

4.   deformaçao a frio;

5.   presença de molibdenio;

6.   presença de elemento, com forte afinidade pelo carbono.

1.   Tempo de permanencia dentro da faixa crítica de temperaturas.
O tempo de permanencia durante o qual o aço austenítico inoxidável é mantido dentro da faixa crítica de temperaturas desempenha um importante papel. Com efeito, foi verificado, experimentalmente, que, a uma dada temperatura da faixa crítica, a variaçao da tendencia a corrosao com o tempo de permanencia se dá com um máximo, isto é, ela cresce inicialmente, atinge um máximo e depois decresce até o desaparecimento total da corrosao (20). A Fig. 23 ilustra o fenomeno, que pode ser explicado tendo por base a segunda teoria. De fato, a quantidade de carbonetos precipitados aumenta com o tempo e, em consequencia, aumenta também a quantidade de cromo retirada do grao. Como a difusao do cromo é mais lenta que do carbono, haverá um empobrecimento em cromo, na regiao periférica do

grao, sempre mais acentuado e, portanto, uma maior diferença de poten-
cial. Porém, após um certo tempo, a precipitação dos carbonetos alcança
rá o equilibrio, e, entao, a partir desse momento haverá uma difusao nos
graos, no sentido de nivelar o seu teor em cromo. Quando isto for alcan-
çado, desaparecerá a diferença de potencial entre o núcleo e a periferia
do grao, restando apenas a diferença de potencial entre o grao e os carbo
netos do seu contorno. Os carbonetos apresentam um potencial eletroquí-
mico mais elevado do que o grao de modo que este último tornar-se-á
anódico. No entanto, sendo a sua área muito grande, relativamente a área
dos carbonetos de contorno, a corrosao resultante dessa diferença de po-
tencial se tornará desprezível.

A cada temperatura dentro da faixa crítica corresponde um tempo
de aquecimento mínimo Z, necessário para que o aç: se torne susceptível
a corrosao intergranular. Esse tempo pode ser corr∍lacionado com a tem
peratura de aquecimento T (em graus absolutos) pela seguinte expressao(20):

$$\log Z = \frac{C}{T}$$

onde C é uma constante do aço. O valor de Z varia também com a veloci-
dade de resfriamento após a solubilizaçao: quanto mais rápido o resfria-
mento maior o tempo necessário para um aço austenftico tornar-se sus-
ceptível a corrosao intergranular (20). A Fig. 24 indica a variaçao de Z
com a temperatura de um aço inoxidável austenftico 18/8 resfriado (após
a solubilizaçao) de dois modos distintos. A disponibilidade desse tipo de
curvas é útil na determinaçao da soldabilidade dos diferentes aços austenf
ticos.

Essa variaçao de Z com a velocidade de resfriameuto (após a solu
bilizaçao) pode ser explicada tendo em vista que a precipitaçao de consti-
tuintes nos contornos dos graos é um processo de nucleaçao e crescimento.
A passagem, pela faixa crítica de temperaturas, implica no aparecimento
de um certo número de núcleos que é tantc maior quanto maior for o tem-
po de permanencia do aço nossa faixa. Assim, un resfriamento mais lento
promoverá a formaçao de um apreciável número de núcleos que, posterior
mente, quando do novo aquecimento, já sofrerao crescimento.

2.   Teor de carbono
A susceptibilidade, de um aço inoxidável austenftico a corrosao in
tergranular, varia, quase linearmente, com o seu teor de carbono (18)(20).
Isto é de se esperar, uma vez que o carbono é um dos principais constituin
tes dos precipitados dos contornos de grao e, portanto, o responsável dire
to pela εinsitizaçao. A Fig.25 ilustre a variaçao da corrosao intergranular
com o teor de carbono de um aço 18/8. Note-se que, abaixo de 0,03% de

carbono, a corrosao é praticamente desprezível. No entanto, esse valor nao pode ser considerado como limite de separaçao entre a susceptibilida de e nao-susceptibilidade a corrosao intergranular, pois o mesmo varia com os demais fatores.

3. Tamanho de grao

Aços inoxidáveis austenfticos com graos grandes sao mais suscep tíveis a corrosao intergranular do que aqueles com tamanho de grao pequeno (20). Isso se deve, provavelmente, ao fato de que com o aumento do tamanho de grao a relaçao entre a área catódica e anódica também aumenta, resultando, em consequencia, um aumento de densidade de corrente na área anódica.

4. Deformaçao a frio

A deformaçao a frio dos aços inoxidáveis austenfticos, previamente solubilizados, diminui fortemente a sua tendencia a corrosao intergranular(20). Uma deformaçao a frio acima de 15% encarrega-se de "abrir" os planos de escorregamento dentro dos graos, de modo que, quando o aço for aquecido para dentro da faixa crítica, a precipitaçao de carbonetos se dará de prefe rencia ao longo desses planos e nao dos contornos. Em face disso, resulta rá uma dispersao dos carbonetos dentro dos graos com consequente diminuiçao da susceptibilidade a corrosao intergranular.

5. Presença de molibdenio

Aços inoxidáveis austenfticos, com 1 a 3% de molibdenio, sao menos susceptíveis a corrosao intergranular do que os que nao o contém (20). O molibdenio, sendo um componente estabilizador da ferrita, favorece a for maçao da estrutura austenito-ferrítica no aço. No entanto, a presença de ferrita favorece a precipitaçao da fase sigma nos contornos de grao que atua de modo semelhante a dos demais precipitados no que se refere a cor rosao. Desse modo, a adiçao de molibdenio a um aço austenítico inoxidá vel nao resolve o problema de sensitizaçao, porém apenas a diminui ligeramente.

6. Presença de elementos com forte afinidade pelo carbono

A adiçao de certos elementos aos aços inoxidáveis austenfticos, co mo por exemplo, titanio, columbio e tántclo (10) (20), aumenta considera-velmente a sua resistencia a corrosao intergranular. Esses elementos apresentam uma afinidade pelo carbono maior do que o cromo, de modo que, os carbonetos que precipitam sao de preferencia desses elementos.

Desse modo, o cromo permanece em soluçao sólida, evitando a formaçao de gradientes de concentraçao que sao responsáveis pela corrosao inter-granular. Pelo fato de conferirem aos aços grande resistencia a corrosao intergranular esses elementos sao chamados de "estabilizadores" e o aço que os contem é chamada "estabilizado".

IV.3   Medidas para eliminar a corrosao intergranular.

Quando um aço inoxidável austenítico é utilizado em condiçoes em que ele nao sofre aquecimento para dentro da faixa crítica de temperaturas, nao há neces sidade de nenhuma medida no sentido de eliminar a sua susceptibilidade a corrosao intergranular, sendo suficiente apenas um tratamento de solubilizaçao na faixa de temperaturas de 1050 a 1100º C, seguido de resfriamento brusco. A solubilizaçao encarrega-se de dissolver todos os carbonetos de contorno e o resfriamento brus-co evita a sua re-precipitaçao (18). No entanto, estes tratamentos térmicos nao podem ser aplicados a peças grandes, ou, entao, peças que nao possam tolerar escamas e empenamentos que ocorrem nesses tratamentos.

Para esse tipo de peças, e para peças que sao aquecidas para dentro da faixa crítica, há necessidade de se adotar uma ou uma combinaçao das seguintes medidas:

1.   Reduzir o teor de carbono ao mínimo possível.

2.   Manter um pequeno tamanho de grao.

3.   Promover deformaçao a frio após a solubilizaçao e depois aquecer para dentro da faixa crítica no sentido de promover a precipitaçao dos crbonetos ao longo dos planos de escorregamento.

4.   Aquecer a peça dentro da faixa crítica, longe de agentes corrosi-vos, por tempo suficiente para promover a homogeinizaçao do cro mo dentro dos graos.

5.   Adicionar ao aço elementos estabilizantes (titanio, colúmbio e tán talo).

De todas essas medidas, as mais largamente utilizadas sao a prime. i e a última.

IV.4   Exemplos: Dois casos de corrosao intergranular

IV.4.1. Corrosao de um tubo de aço inoxidável empregado na proteçao de uma resistencia elétrica

Trata-se de um caso de corrosao intergranular ocorrido com um tubo de aço inoxidável AISI 316 utilizado na proteçao de uma resistencia elétrica (21). Esse tubo trabalhou mergulhado, até sofrer ruptura, num banho de sal fundido de um forno de tratamentos térmicos, durante cerca de 20 horas. A temperatura do trabalho do banho era em média de 270º C. O sal era um combinaçao de nitrito de sódio, nitrato de sódio e nitrato de potássio e continha, além disso, quantidades apreciáveis de cloretos.

O exame do tubo permitiu verificar que a sua corrosao foi generalizada em toda a superfície externa, que estava em contato com o banho. A corrosao foi tipicamente intergranular, conforme pode ser observado nas Figuras 26 e 27. A Fig. 27 mostra, além disso, presença de carbonetos em contorno de grâu que, na realidade, nao estao muito nítidos em virtude do baixo teor de carbono do aço.

Em face do exposto conclui-se que se trata de um caso de sensitizaçao do aço. Encontrando um meio razoavelmente corrosivo, uma vez que os cloretos constituiam parcela apreciável dentro do sal, e tendo em vista a temperatura de trabalho, o tubo sofreu forte corrosao, chegando a ruptura. Deve-se notar que, apesar da temperatura de trabalho do banho ter sido de 270º C, a temperatura do tubo foi consideravelmente superior, em virtude do gradiente térmico que ocorreu nessas condiçoes.

IV.4.2. Corrosao de um anel de aço inoxidável utilizado num equipamento químico

Trata-se de um caso de sensitizaçao devida a solda, ocorrido com um anel de aço inoxidável austenítico AISI 302. (22) Este anel apresentava duas soldas longitudinais e trabalhava em contato com ácido sulfúrico em equipamento químico.

A corrosao desenvolveu-se apenas nas regioes vizinhas as soldas, conforme pode ser visto na Fig. 28, e, além disso, foi tipicamente intergranular, segundo mostra a Fig. 29. A precipitaçao de carbonetos nos contornos dos graos foi confirmada por exame metalográfico.

V.   FRATURA POR CORROSAO SOB TENSAO

V.1.   Características gerais

Se um metal ou liga está submetido a uma tensao de traçao estática consi
derável, num meio agressivo, podemos ter simplesmente uma aceleraçao do pro
cesso corrosivo. Entretanto, em certas condiçoes, pode dar-se o aparecimento
de um fenomeno de características diferentes, que recebe o nome de "fratura por
corrosao sob tensao" ("stress corrosion cracking"). Este fenomeno se caracteri
za pelo aparecimento e posterior desenvolvimento de trincas que conduzem a rup
tura do metal.

O tempo necessário para que haja a ruptura depende da tensao de traçao
aplicada, da agressividade do meio e da liga utilizada.

A corrosao sob tensao assume características próprias para cada liga e
para cada meio corrosivo. Podemos enumerar, entretanto, características comuns
a todos os casos:

1.   A fratura causada pela corrosao sob tensao, em geral, nao apre-
senta estricçao e o aspecto é semelhante do dado por fadiga. Com
a propagaçao progressiva da trinca resulta uma diminuiçao na secçao re-
sistente até ser atingido o limite de resistencia do material. Desse modo,
aparecem na fratura duas zonas distintas: a primeira, mais lisa, corres-
pondendo a trinca propagada e a segunda, de aspecto rugoso e grosseiro,
correspondendo a ruptura brusca.

2.   A corrosao sob tensao só se manifesta quando há a açao simultanea
.. .: de considerável tensao de traçao e de um meio corrosivo. Isto sig-
nifica que nao haverá ruptura se mantiver-mos sob traçao, em meio nao
corrosivo, um material previamente corroído (23).

3.   Tensoes de compressao nao causam rupturas. Ao contrário, a in-
troduçao de tensoes de compressao na superfície de um metal ou li
ga pode prevenir o trincamento devido a corrosao sob tensao.

4.   As rupturas podem ser devidas tanto as tensoes internas residuais
quanto as tensoes externas aplicadas.

5.   As trincas podem ser intergranulares, transgranulares ou mistas.
Uma trinca originada por um processo corrosivo intergranular terá
um desenvolvimento predominantemente intergranular. Por outro lado um
ataque corrosivo, que se dá no corpo do grao, dará uma trinca de desenvol

vimento transgranular (24).

6.   A corrosao é, em geral, altamente localizada. isto significa que
        podemos ter peças trincadas ou rompidas por corrosao sob tensao
sem que a superfície das mesmas denote evidencia de processo corrosivo
generalizado.

7.   As trincas se desenvolvem perpendicularmente a direçao do esfor-
        ço de traçao.

8.   Em muitos casos tem-se observado a existencia de uma tensao mí-
        nima baixo da qual nao se verificam rupturas num tempo finito bas-
tante grande (Fig.36).

V.2.   Mecanismo do trincamento por corrosao sob tensao

        O aparecimento e a propagaçao de trincas num material metálico, corroí
do sob tensao, é um fenomeno complexo resultante de açoes mecanicas e eletro-
quimicas simultaneas.

        As tensoes mecanicas, além de serem diretamente responsáveis pel propa
gaçao da trinca e consequente destruiçao dos materiais, modificam também o
seu comportamento eletroquimico.

        Para explicarmos o mecanismo do trincamento por corrosao sob tensao
devemos considerar cada um dos dois estágios em que se pode dividir o processo,
a saber, a formaçao da trinca e a sua posterior propagaçao.

a)   Formaçao da trinca

        A formaçao da trinca se deve a um ataque corrosivo localizado.
Este ataque pode se dar em:

        1.   áreas anódicas nos contornos de grao que sao devidas a pre
                sença de precipitados, ao alto acúmulo número de defeitos
                cristalinos ou a concentraçao de tensoes;

        2.   Pontos de ruptura do filme superficial de óxido;

        3.   áreas anódicas devidas a deformaçao plástica, podendo se
                ter inclusive a precipitaçao de fases meta-estáveis;

4. áreas de contornos sub-estruturais nas quais podemos ter uma segregaçao de átomos de soluto ou acúmulo de defeitos cristalinos (25)(26).

b)   Propagaçao da trinca

A propagaçao da trinca tem como explicaçao mais plausível uma teoria mecanica. A concentraçao de tensoes no fundo de uma fissura inicialmente formada pode provocar, em certos pontos, a deformaçao plás tica com a consequente propagaçao da trinca. A deformaçao plástica provoca ainda a ruptura do filme protetor. O meio corrosivo que penetra na fissura acelera a propagaçao da trinca. Assim, se por qualquer motivo for interrompida a propagaçao, o ataque corrosivo no interior da fissura reiniciará o processo. As trincas maiores possuem tendencia de se propagarem mais rapidamente que as menores. Assim que uma trinca se torna dominante ela interrompe o desenvolvimento de outras.

A velocidade de propagaçao de uma trinca aumenta em progressao geométrica com o tempo (Fig.31)(26).

V.3   Exemplo: Corrosao sob tensao de barras protendidas.

Com a generalizaçao do emprego de concreto protendido na construçao civil, um bom número de casos de rupturas de barras, devidas a corrosao sob tensao, tem surgido, uma vez que as barras das armaduras sao empregadas sob tensoes de traçao próximas do limite de escoamento. Nestas condiçoes um meio mais agressivo poderá causar graves danos a estrutura. É o caso do concreto que contém cloreto de cálcio como acelerador da pega. Este componente tem se revelado um agente danoso na corrosao sob tensao(27).

A presença de nitratos também tem provocado o fenomeno (29).

O gás sulfídrico é mais drástico, devido a difusao de hidrogenio no reticulado, provocando assim fragilizaçao localizada (28).

A proteçao imperfeita da barra ou arame pelo concreto pode também favorecer forte ataque corrosivo.

Além das condiçoes do meio, influem também sobre a resistencia do material a natureza e tratamento do mesmo. Assim, material temperado é em geral

sensível a corrosao sob tensao (30). Por outro lado, barras encruadas e aliviadas de tensao possuem melhor resistencia (27).

Passaremos a descrever, em seguida o caso de arame empregado na armadura de tubo protendido na segunda adutora de Ribeirao das Lajes e que foi enviado ao I. P. T. para determinaçao da causa de fratura (31).

Este arame foi aplicado sob tensao, sobre uma camisa de aço, que por sua vez revestia um tubo de concreto com espessura média de o cm. O tubo tinha o diametro de 1,75m e o arame era aplicado em espiral em torno dele. Nas extremidades o arame era preso por meio de luvas que eram soldadas a camisa. As emendas, quando necessárias, eram feitas através de luvas especiais. Os tubos assim protendidos eram revestidos externamente por uma argamassa a fim de proteger a camisa e o arame contra a corrosao. A Fig. 32 mostra um desses tubos com argamassa parcialmente removida.

As rupturas tiveram. início depois dos tubos estarem em serviço por mais de 4 anos e se deram no trecho de pressao máxima da linha (80 m de água). O aspecto das fraturas resultantes encontra-se na Fig. 33.

Nas amostras recebidas constatou-se que certas porçoes do arame eram francamente quebradiças e se rompiam ao serem dobradas, enquanto que outras suportavam flexao manual forte.

Na fratura, a regiao correspondente a trinca é escura (devido a corrosao) enquanto que a regiao rompida bruscamente por flexao é mais brilhante.

Uma porcentagem muito pequena do arame rompeu com estrangulamento pronunciado, caracteristico de material tenaz rompido por traçao, com pequeno alongamento e grande estricçao.

Observaçoes preliminares feitas com lupa ao longo de numerosas amostras do arame pertenecentes aos tubos rompidos, revelaram a existencia de trincas transversais, conforme pode-se observar nas Figuras 34 e 35. A Fig. 36 apresenta detalhes de duas trincas da Fig. 35.

As observaçoes, feitas nos tubos rompidos, revelaram que nos locais em que a ruptura do arame provocou a fissuraçao da argamassa protetora, o arame se apresentava enferrujado. Entretanto, em outros locais, onde a ruptura do arame nao provocou a fissuraçao da argamassa, nao foi notada a presença de ferrugem a nao ser na secçao da fratura.

O exame micrográfico do material revelou tratar-se de aço temperado e revenido, nao denotando qualquer anomalia.

Se o arame já estivesse trincado quando da sua ʼplicaçao dificilmente teria resistido a protençao e mais 4 anos de trabalho. Portanto, do acima exposto conclui-se que as trincas surgiram no material depois de instalado. Tendo em vista que o arame estava submetido a considerável tensao de traçao e que as evidencias apresentadas denotaram a possibilidade de um ataque corrosivo, conclui-se que as trincas surgiram e se propagaram devido ao fenomeno de corrosao sob tensao.

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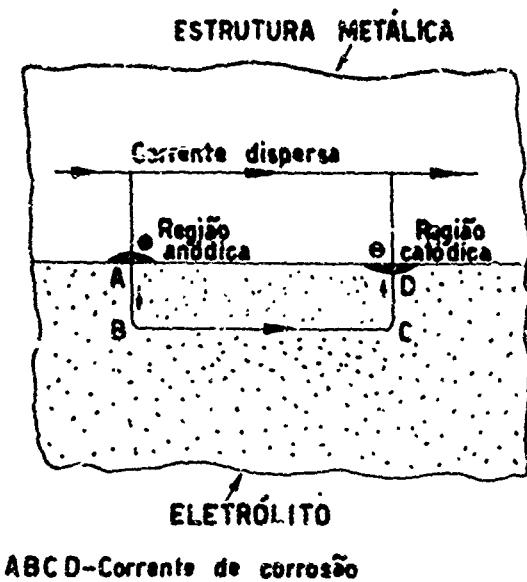
FIG.1   Esquema do mecanismo da corrosão
         por correntes dispersas que passam
         pela estrutura.

ABCD-Corrente de corrosão

ABCD – CORRENTE DE CORROSÃO
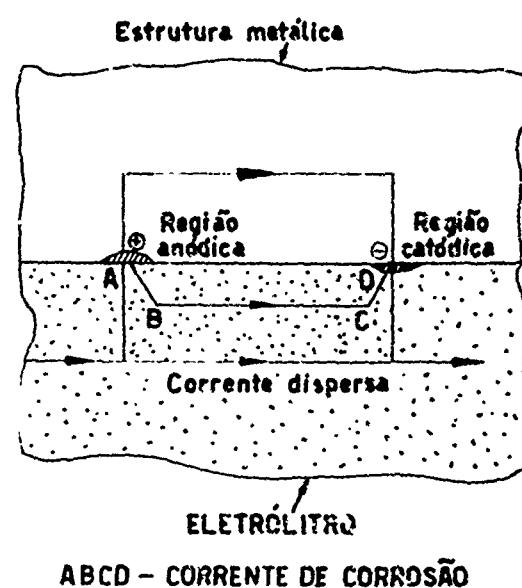
FIG.2   Esquema do mecanismo da corrosão
         por correntes dispersas que passam
         pelo eletrólito.
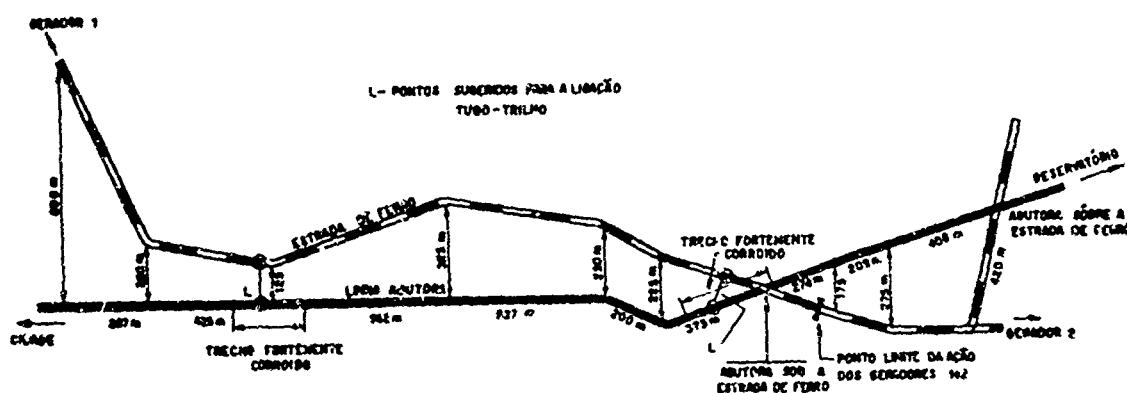
FIG.3   Disposição da estrada de ferro em
         relação à linha adutora.

FIG. 4   Esquema do perfil da linha adutora de água na região em que se observou a corrosão mais intensa.
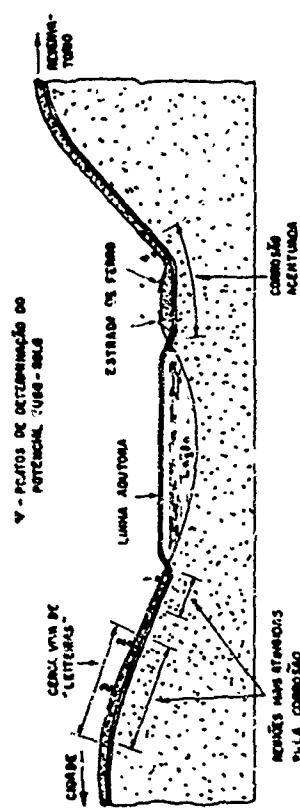
FIG. 5   Aspecto da erosão causada pelo vazamento de água através dos furos provocados pela corrosão. Observe-se o jato de água que sai por um furo destapado.
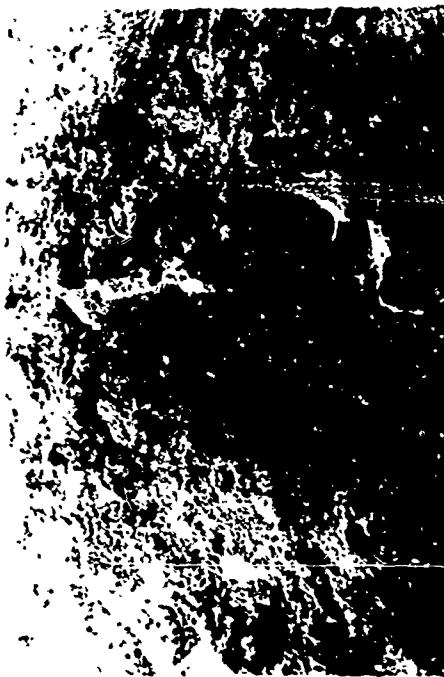
FIG. 6   Furo causado pela corrosão e tapado com um pino de madeira.

FIG. 7

Protuberâncias causadas na camada asfáltica externa pela corrosão alveolar.

FIG. 8

Mesma região da Fig. 7 após a remoçao da camada asfáltica externa de um dos alvéolos e do produto de corrosão nêle contido.

FIG. 9

Aspecto da corrosão alveolar bem avançada em três pontos próximos. O alvéolo da direita localiza-se na parte superior do tubo colocado horizontalmente. Os outros dois estão na mesma secção transversal. O revestimento asfáltico foi removido a fim de melhor observar-se a corrosão.
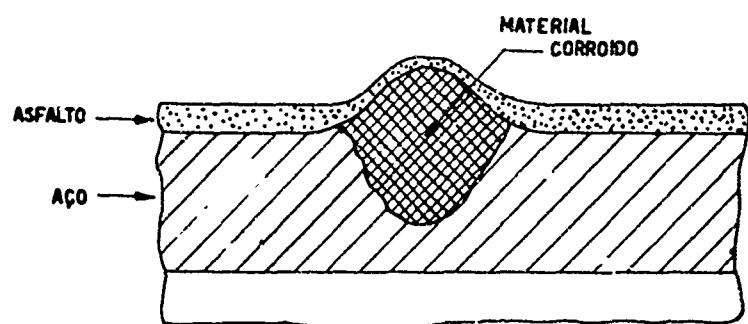
FIG.10   Esquema de um alvéolo de corrosão.
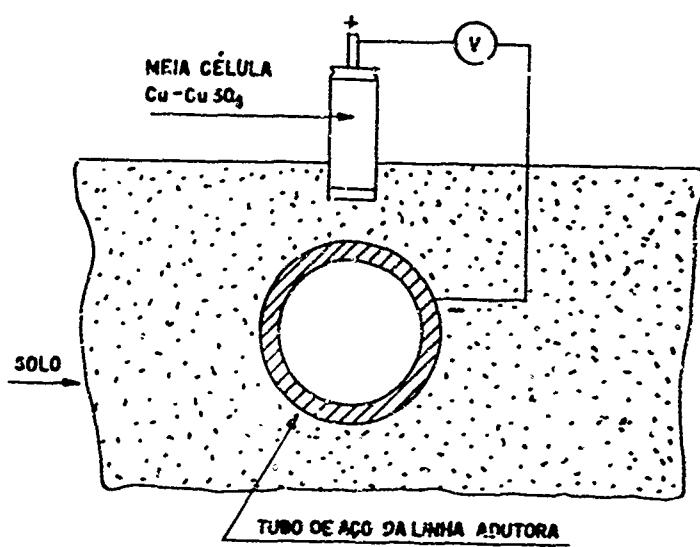
FIG.11   Esquema da disposição utilizada para a
determinação do potencial tubo-solo.
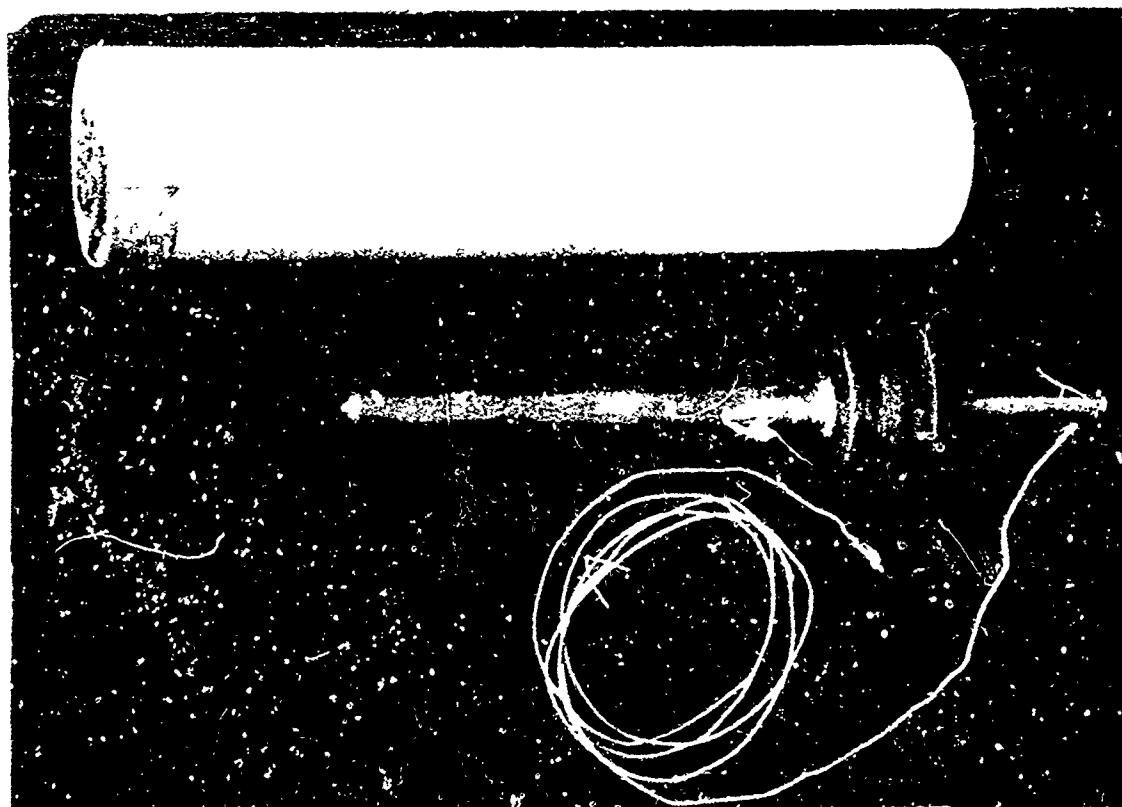
FIG.12   Meia célula de (cobre)-(sulfato de cobre)
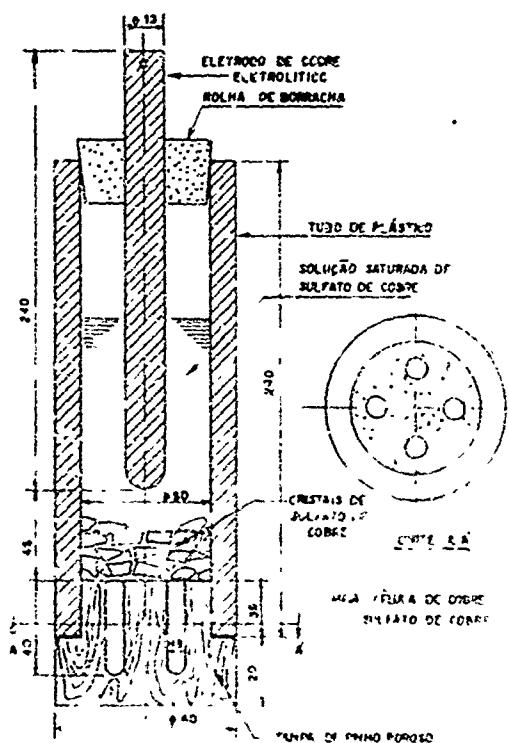
FIG.13   Desenho da meia célula de (cobre)-
            (sulfato de cobre)
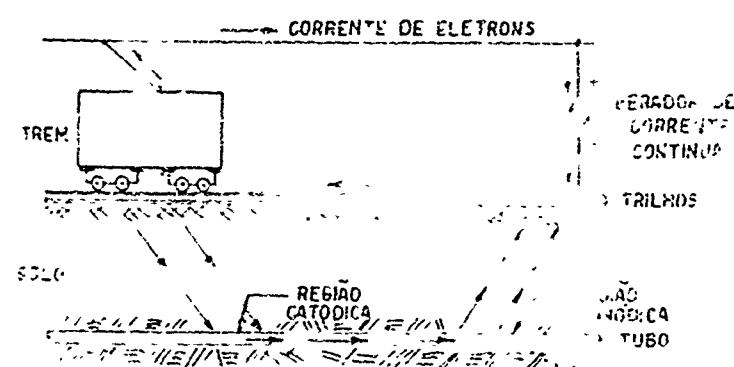
FIG.14   Esquema da situação que e . oum à
            corrosão por corrente. o . . .as dos
            tubos enterrados.

FIG.15   Esquema da ligação tubo-trilho com em-
prêgo de um transformador-retificador.
(Ref.(1), pág. 263).
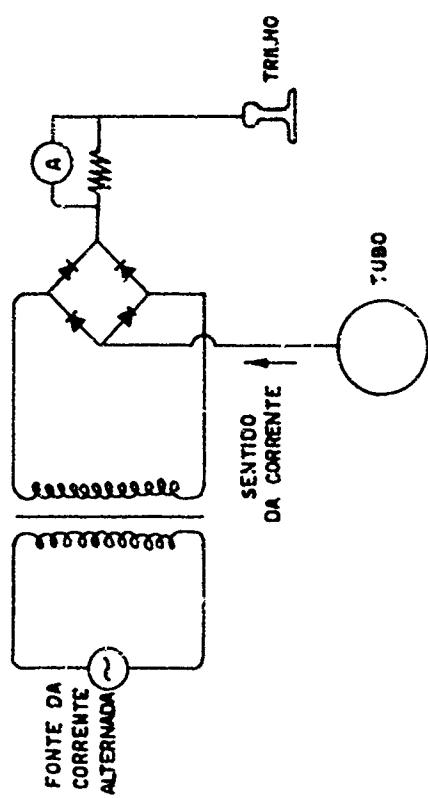
FIG.16   Ilustração da formação de uma célula de
concentração de oxigênio devida ao conta_
to entre dois materiais em presença de
um eletrólito.
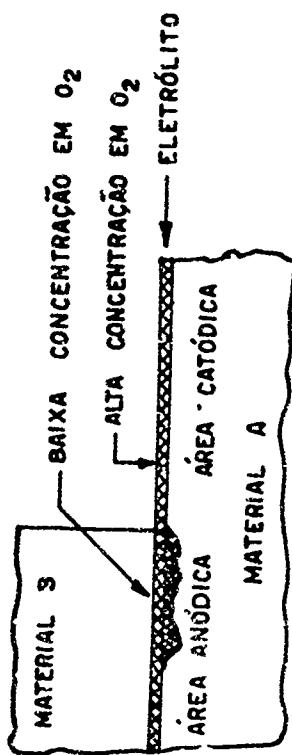
FIG.17   Corrosão em frestas devida à formação
de uma célula de concentração de cobre.
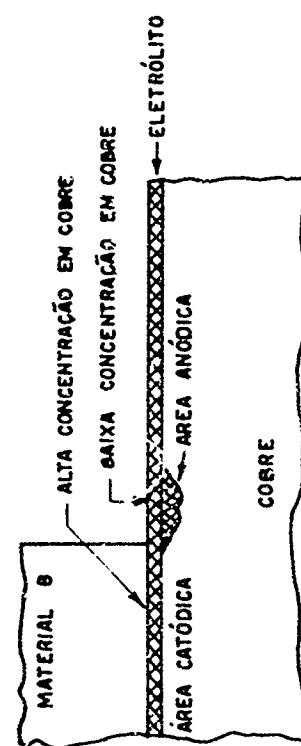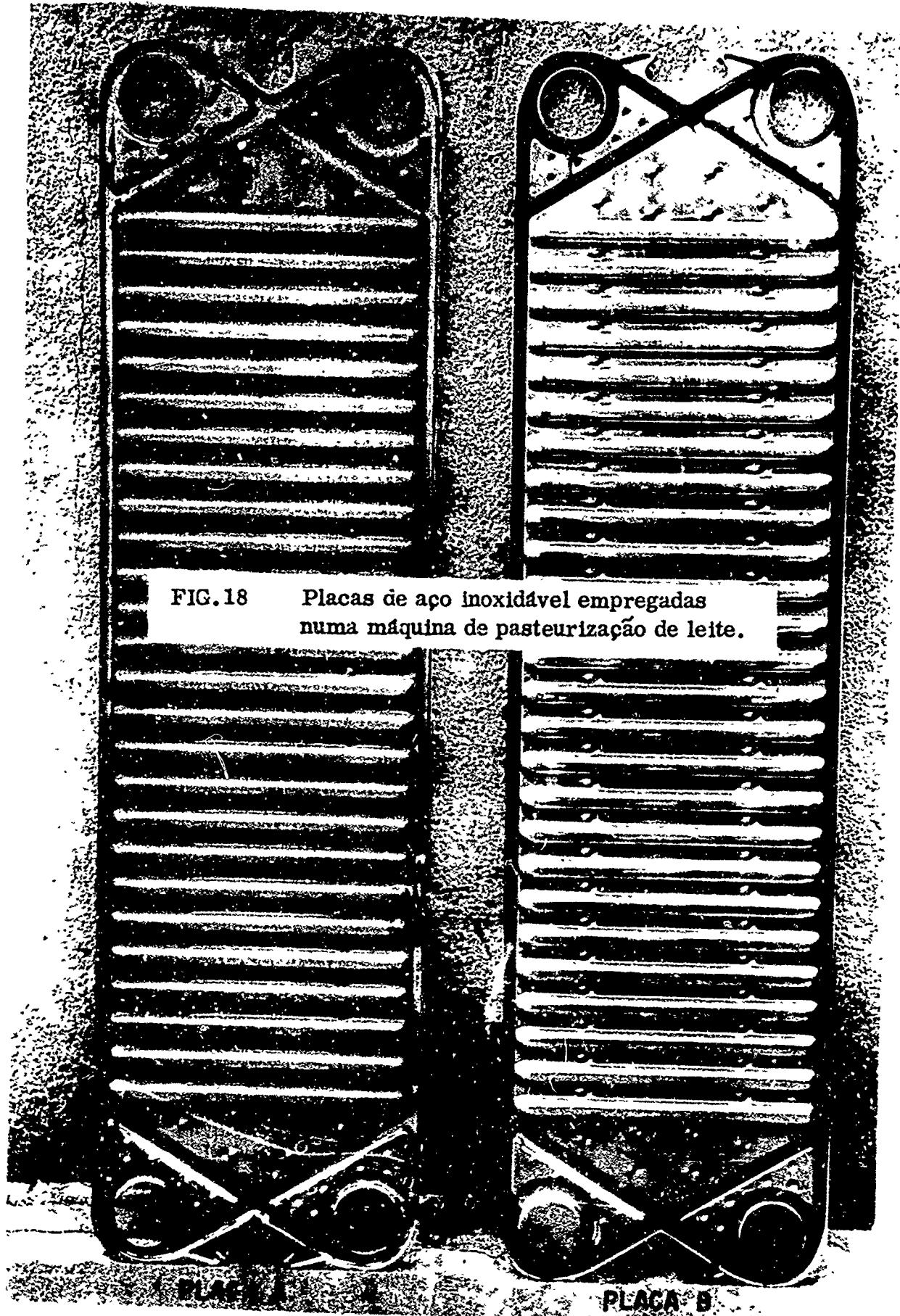
FIG. 18   Placas de aço inoxidável empregadas
numa máquina de pasteurização de leite.
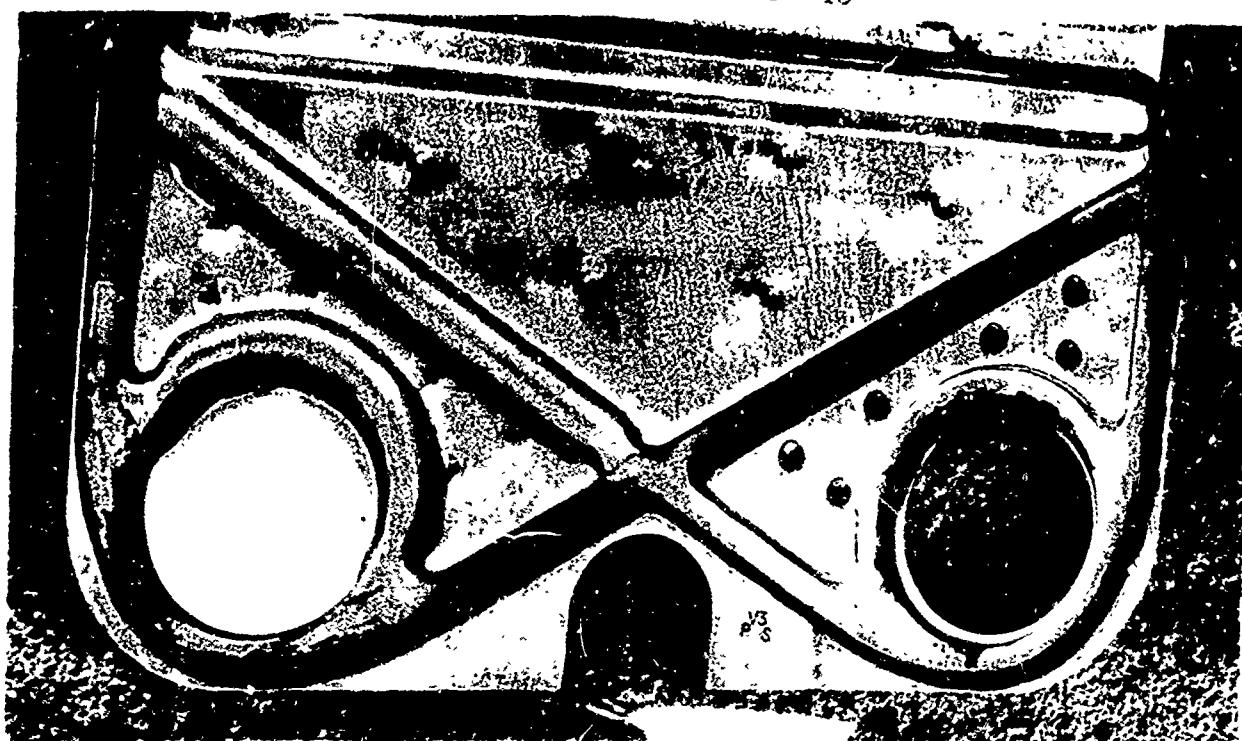
FIG. 19   Corrosão alveolar dentro da canaleta
            circundante do furo de alimentação da
            salmoura.

FIG. 20   Secção diametral de um alvéolo da Fig. 19
            Ampliação de 50 diametros.
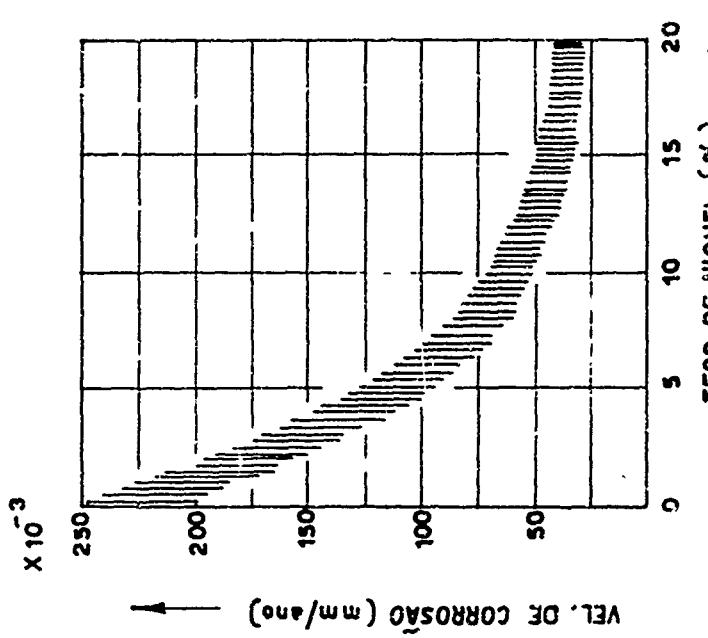
FIG. 21

Variação da resistência à corrosão de aços inoxidáveis com 15% de cromo em função do teor de níquel. A área hachureada inclui todos os valôres obtidos em ensaios de 20 horas, a 30º C, realizados em água do mar cr m-pletamente aerada e ativada, em uma solução de 5% de NaCl e em uma solução de 20% de CaCl$_2$)(Ref. (14), pág 43).
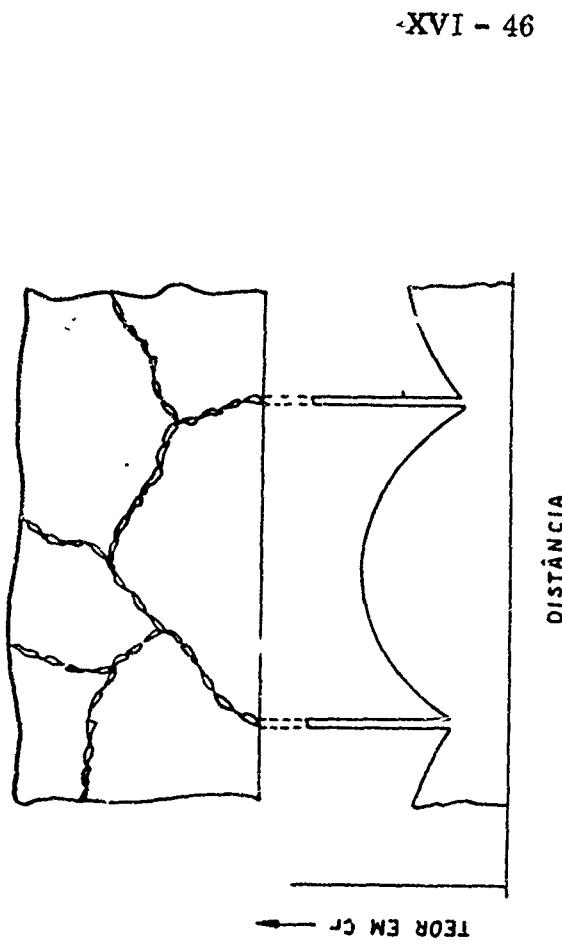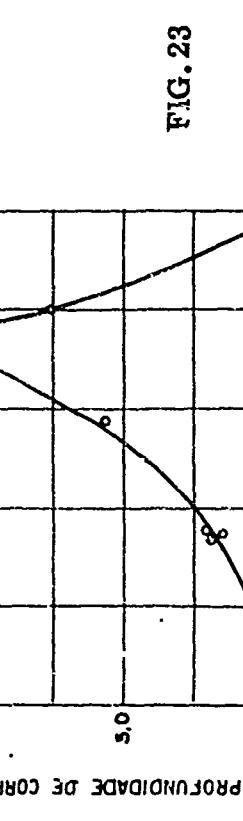
FIG. 22

Variação do teor de cromo entre o interior e o contôrno dos grãos, causada pela sensi tização.

FIG. 23

Profundidade de corrosão intergranular de um aço 18/8 (contendo 0,08% de carbono e prèviamente solubilizado) em função do tempo de aquecimento a 650º C. A profun-didade de corrosão foi medida após 100 horas de perma-nência em uma solução ácida de sulfato de cobre. (Ref. (20), pág. 94).

FIG. 24 — Tempo necessário para sensitização do aço inoxidável 18/8 em função da temperatura de aquecimento, e após dois diferentes tratamentos prévios: 1-aquecimento a 1100ºC e resfriamento ao ar; 2-aquecimento a 1100ºC e resfriamento em água. (Ref.(20), pág. 95).
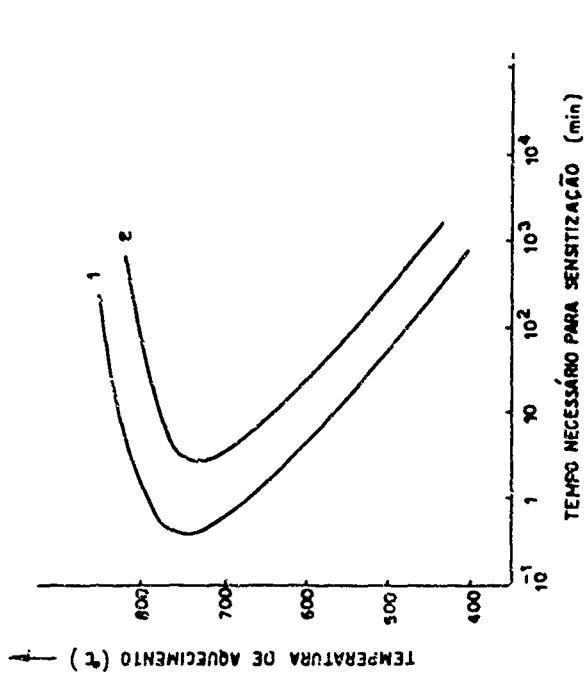
FIG. 25 — Efeito de teor de carbono sôbre a máxima penetração da corrosão intergranular de um aço 18/8 solubilizado após 1000 horas a 800ºC e 100 horas em solução ácida de sul_fato de cobre. (Ref.(20), pág. 93).
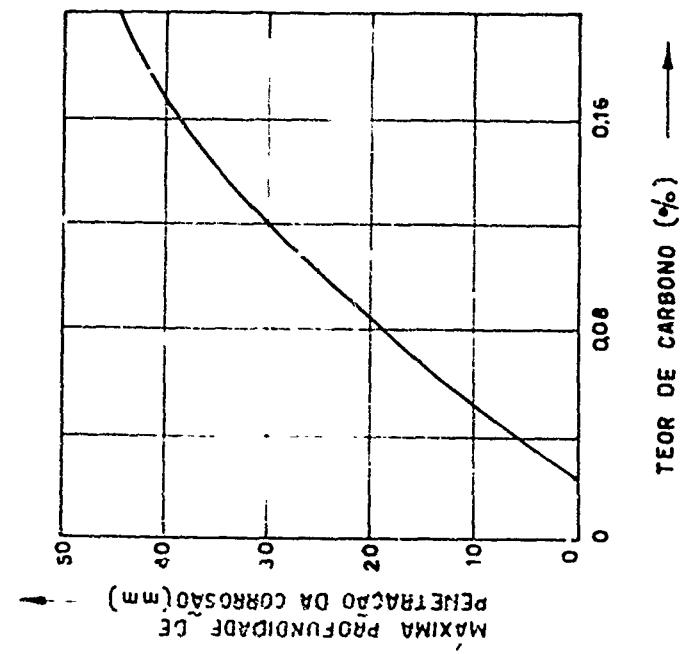
FIG. 26 — Corrosão intergranular de um tubo de aço inoxidável austenítico AISI 316. Secção transversal. Sem ataque. Ampliação de 200 diâmetros.

FIG. 27   Mesmo aço da Fig. 26. Grãos de austenita e carbonetos em contornos de grão. Corrosão intergranular na parte inferior. Secção transversal. Ataque: água+régia. Ampliação de 1000 diâmetros.

FIG. 28   Aspecto do desenvolvimento da corrosão nas regiões vizinhas a uma das soldas do anel de aço inoxidável AISI 302. Secção transversal. Ataque: ácido cloridrico. Ampliação de 10 diâmetros.

FIG. 29   Corrosão intergranular do anel de aço inoxidável na região da solda. Secção transversal. Sem ataque. Ampliação de 200 diâmetros.
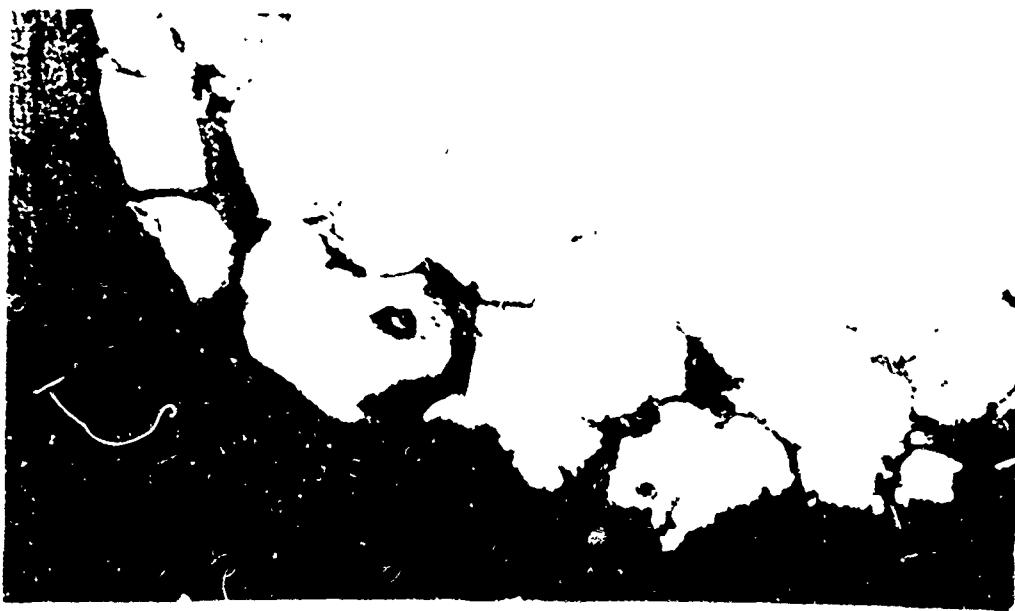
FIG. 30   Tempo decorrido antes da ruptura em função da tensão aplicada. (Ref. (24), pág. 5).

TENSÃO APLICADA

TEMPO NECESSÁRIO PARA OCORRÊNCIA DE RUPTURA

VELOCIDADE DE PROPAGAÇÃO DA TRINCA
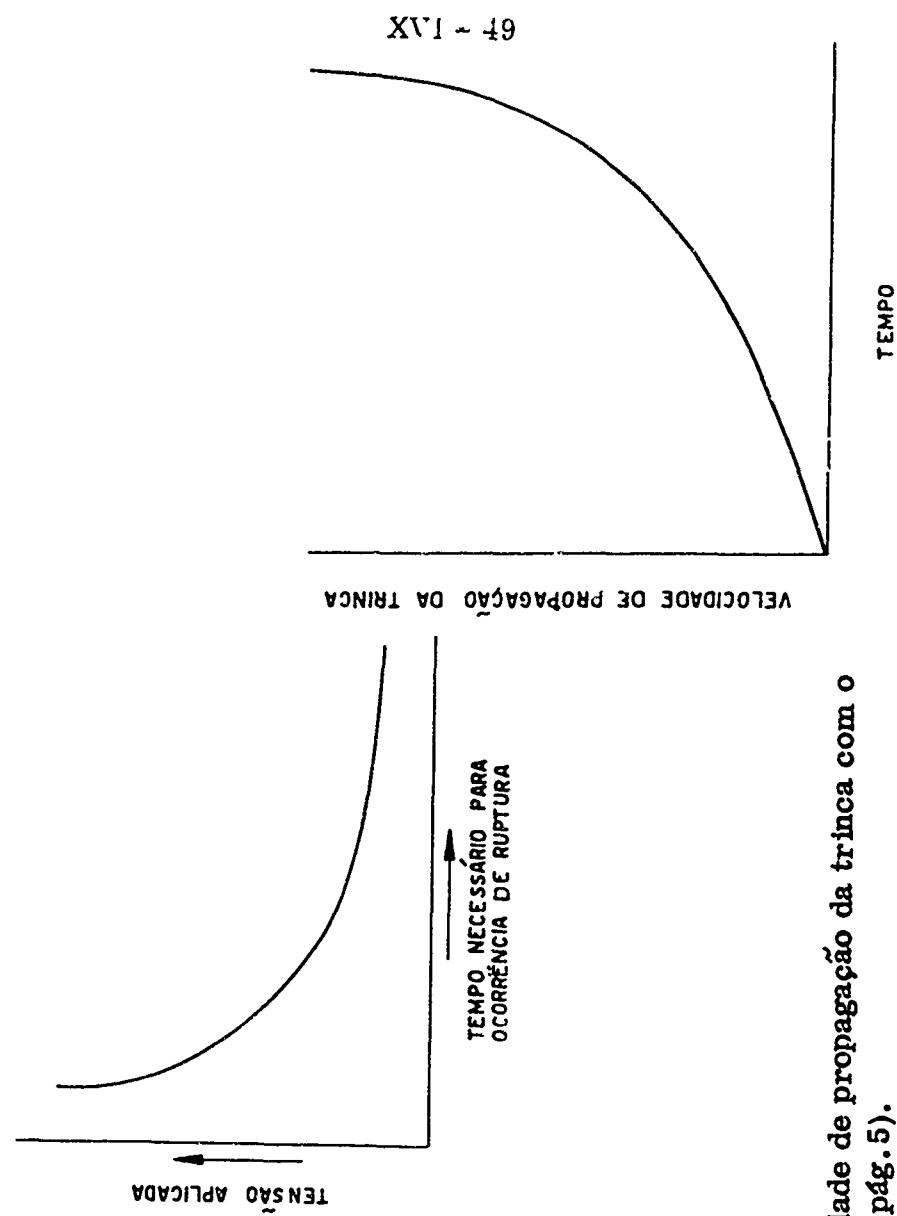
TEMPO

FIG. 31   Aumento da velocidade de propagação da trinca com o tempo. (Ref. (26), pág. 5).

FIG. 32   Tubo com argamassa parcialmente removida,
mostrando arames rompidos.
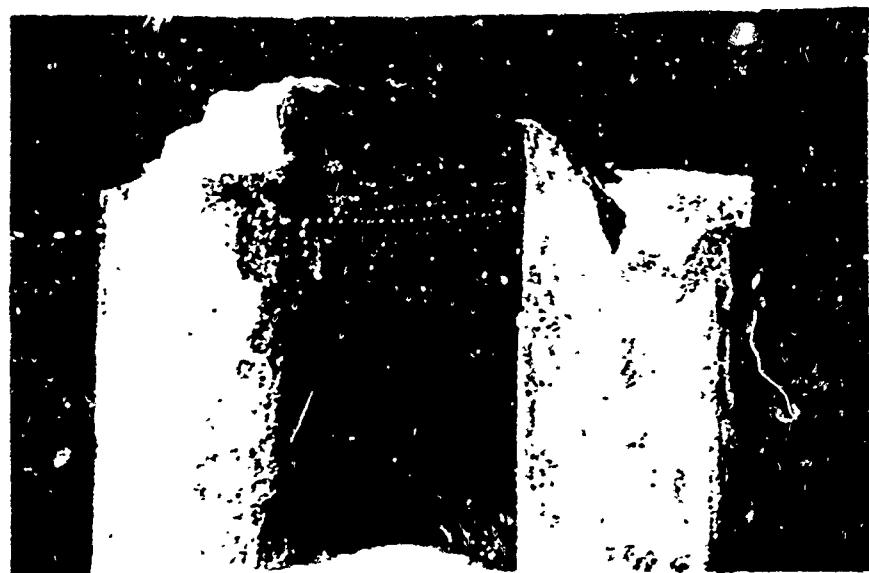
FIG. 33   Aspecto de duas fraturas frágeis observadas.
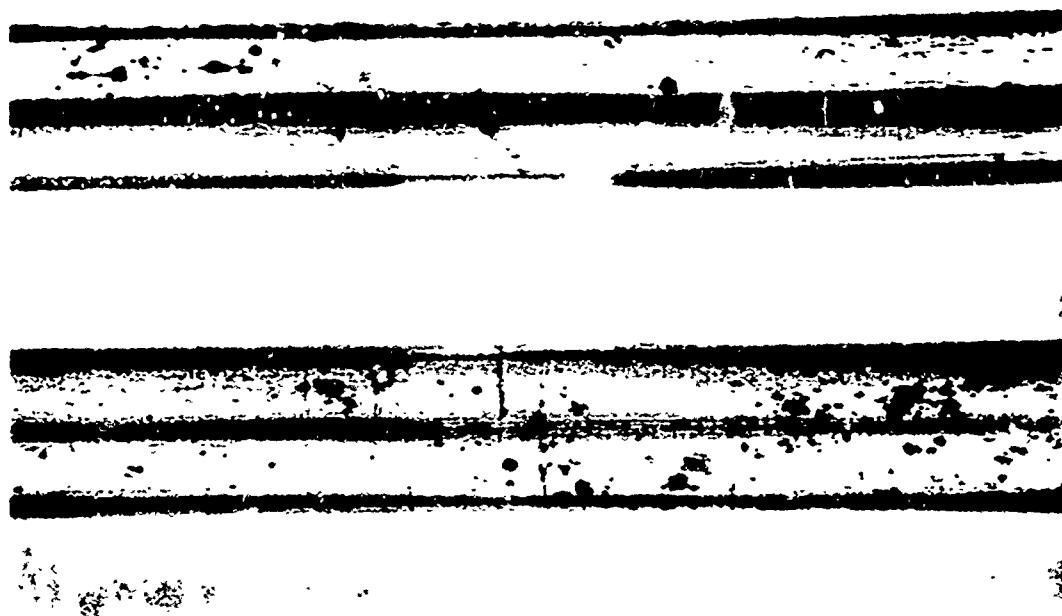
FIG. 34   Aspectos da superfície dos arames.
Ampliação de 4 diâmetros.
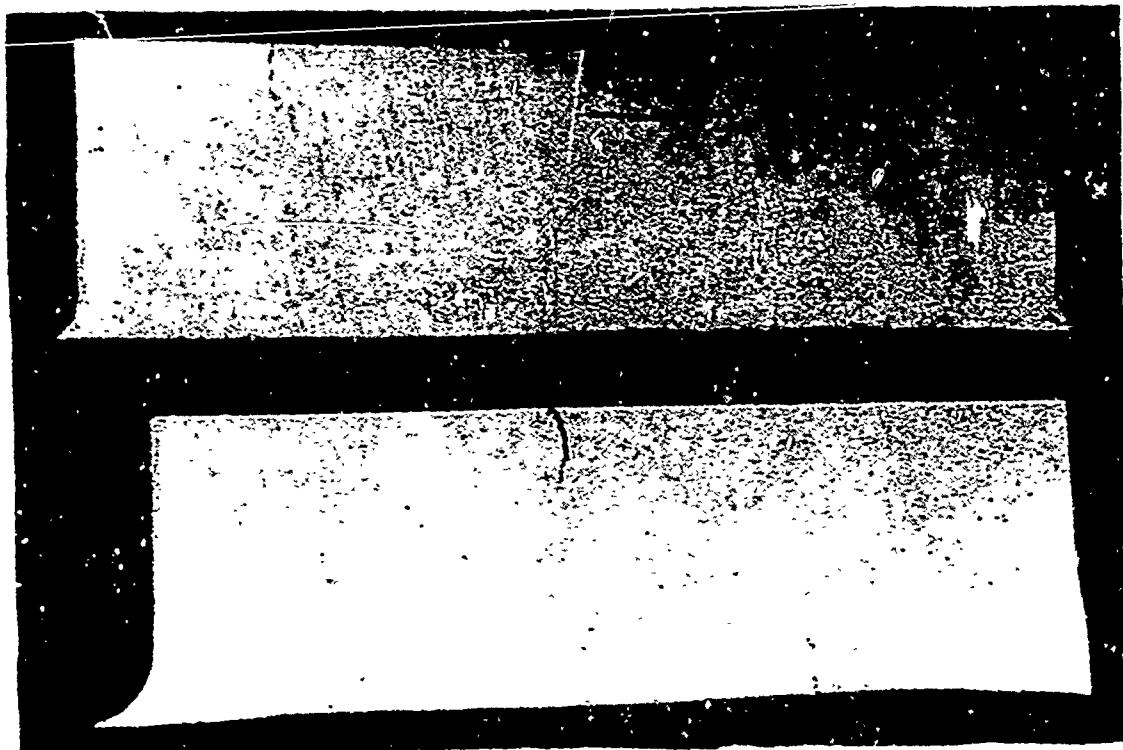
FIG. 35   Fissuras observadas na secção
longitudinal. Ampliação de 7 diâmetros.
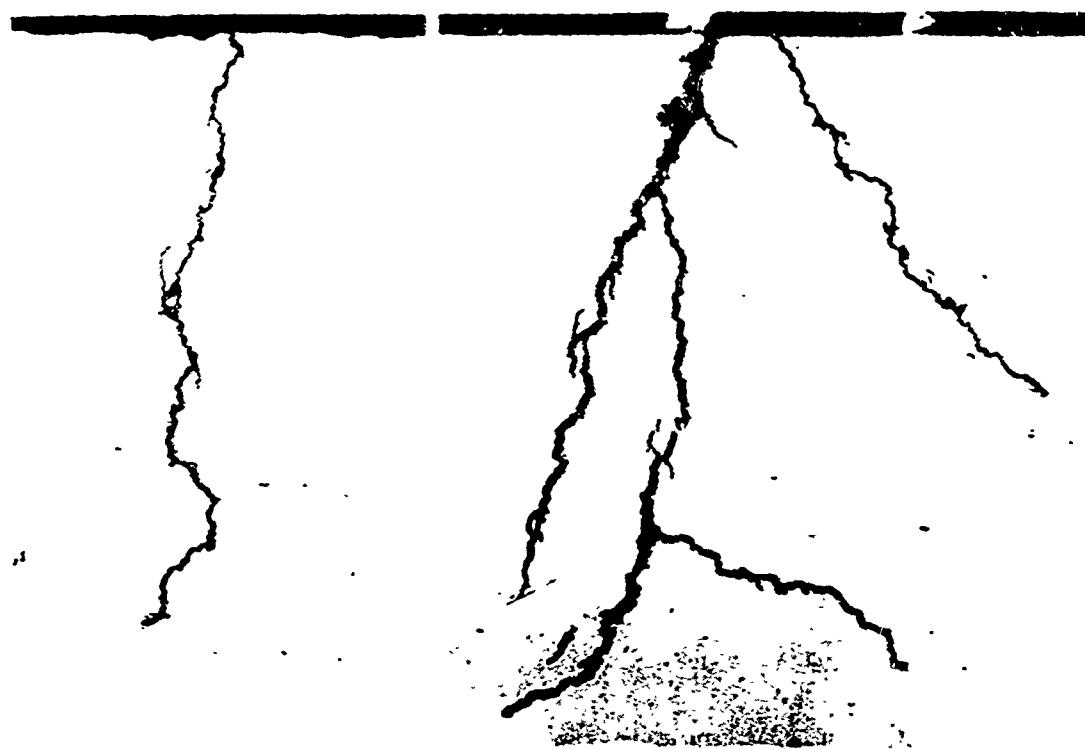
FIG. 36   Detalhes de fissuras da figura anterior.
Ampliação de 80 diâmetros.

FABRICACION DE PLACAS POROSAS

por Luis A. Boschi

Introducción

El objetivo del presente trabajo es la obtención de materiales filtrantes en forma de placas a partir de polvos metálicos y la medición de sus propiedades más importantes. Todo ello contemplando especialmente el problema nacional en cuanto a materias primas y equipos, con miras a ser utilizado por la industria. Se describe además una nueva atmósfera protectora de muy facil producción.

EQUIPO UTILIZADO

Prensa

Se utilizó una pequeña prensa manual capaz de dar una carga de 10 toneladas. La escala se recalibró con un dinamómetro de aro deformable asegurándose las lecturas en 3%.

Matricería

Se usaron dos tipos de matrices: para prensar en frío, fabricadas en acero plata, para pastillas de 20 mm de diam., y para prensar en caliente, fabricadas en acero W K Z de 10 mm de diam. Ambas con pistón superior e inferior móviles para facilitar la extracción de la muestra prensada. La matriz para prensar en caliente tiene un sistema calefactor exterior eléctrico, termostatizado con termocupla y pirómetro de corte automático, algunos detalles pueden observarse en la Figura 1.

Horno

Para el tratamiento térmico en atmósfera reductora, se usó un horno tubu-

lar de 4 cm de diam. y 45 cm de largo, de cuarzo, bobinado con alambre Kantal que permite llegar hasta 1300ºC consumiendo una potencia de 1,2 kw. El sistema está termostatizado con pirómetro de corte automático y termocupla de cromel-alumel. La atmósfera reductora se introduce por una de las tapas de acero inoxidable y sale por la otra, la termocupla de medición y control entra a través de la primera, tapa envainada en acero inoxidable, el cierre hermético de ambas tapas se obtiene con guarniciones de amianto, el gas protector remanente es quemado a la salida, este último detalle permite un control permanente del mismo, ver Figura 2.

Granulometría de los polvos

Se determinó con un equipo de tamices seriados vibratorios del tipo convencional.

Dispositivo para medir el caudal del líquido que pasa a través de la pastilla porosa, en función de la presión de entrada

Fue construído con accesorios comunes de instalación de gas domiciliario, con una cupla de unión de 3/4 pulgada de diam. y dos niples de la misma rosca se armó el sistema esquematizado en la Figura 3, en el cual la pastilla porosa queda entre dos guarniciones de goma, prensada por los niples. Al niple más largo se le soldó con estaño un tubito lateral para acoplarle el manómetro de medida de la presión de entrada, por este mismo niple entra también el agua usada en la medición obtenida directamente de la red de distribución domiciliaria. Las medidas de caudal se hicieron recogiendo el agua de salida en un recipiente de volumen conocido y midiendo el tiempo con un cronómetro.

Dispositivo para medir la carga de rotura

Se construyó en acero, sin templar y de acuerdo al diseño adjunto, Fig. 4, en el cual la pastilla queda firmemente sujeta al apretar la rosca inferior de sujeción, evitándose las pérdidas de presión mediante las guarniciones de goma. En la parte superior se coloca grasa liviana para la uniforme transmisión de la presión y además evitar, por su viscosidad, pérdidas. Para que la grasa no pase a través de la pastilla en ensayo cerramos sus poros con un disco de polietileno delgado (0,2 mm) el cual resiste muy bien la presión ejercida por la grasa pues se apoya contra la pastilla porosa sin entrar en sus poros y además al romperse ésta, no ofrece ninguna resistencia mecánica. Para realizar el ensayo todo el dispositivo es comprimido en la prensa antes citada y la carga de rotura leída en la misma, solo resta calcular el área de la pastilla en ensayo y de ahí deducir la presión específica de rotura.

TRABAJO REALIZADO

Se estudiaron tres materias primas de nuestra plaza y luego de algunos en sayos previos consistentes en: observación microscópica, determinación de granu lometría y compresión en frío, se seleccionó un polvo de bronce provisto por Mer cader (La Plata), que tiene las siguientes características:

Composición química: Cobre 90%

Estaño 9,5%

Zinc 0,5%

Método de obtención: por pulverización en estado líquido, fundido

Observación microscópica: forma prácticamente esférica y muy regular, ver fo-
tomicrografía No. 1.

Determinación de la granulometría y del tamaño de las partículas por medición al
microscopio con micrómetro ocular:

Malla	retenido %	diám. mínimo y máximo	
50	34,4	350	500
70	26,7	250	350
100	19,6	150	250
150	13,6	80	150
200	4,3	70	80
250	0,9	45	70
325	0,23	30	45
menos 325	0,21	menos de 30	

Se hicieron ensayos de compactación en frío con muy mal resultado, las pastillas no tenían cohesión suficiente aún prensadas a 20 ton/cm2 pese a ser ya muy poco porosas. Los ensayos de compactación en caliente hechos a 300ºC y 500ºC dieron prácticamente el mismo resultado solo a 600ºC las pastillas tenían cohesión, pero su densidad aparente se había elevado a 8,5, es decir casi la del bronce, lo cual significa muy pocos poros.

De todo lo anterior se observa que el número de poros es muy pequeño y la tecnología de producción muy compleja, además el prensado en caliente acorta extraordinariamente la vida útil de las matrices. Por lo tanto se intentó usar el "fritage", es decir: la sinterización sin prensado previo, para ello se construyó

una serie de doce matrices cilíndricas con ambas caras desmontables según el diseño adjunto (Fig. 5).

El material usado fue hierro común de caño de gas, para el cuerpo y chapa de hierro para las tapas. Usamos para el tratamiento térmico el horno antes descrito y adoptamos en primera instancia el gas común de cañería domiciliaria (metano 90%, propano 10%) como atmósfera protectora, para ello conectamos directamente la entrada del horno a la red de distribución y quemamos el gas en el caño de salida con una llama luminosa de 5 a 6 cm de alto. Iniciamos la serie de ensayos a la temperatura de 700°C y una hora de tratamiento térmico, esto significa cargar las muestras en el horno frío, comenzar a circular el gas hasta desalojar todo el aire del interior del mismo, conectar la calefacción y al llegar a 700°C mantener dicha temperatura durante una hora, interrumpir la calefacción y dejar enfriar en el horno hasta temperatura ambiente siempre con circulación de gas.

Las mallas usadas en este ensayo fueron: 50, 70, 100 y 150. El resultado no fue nada satisfactorio pues si bien las muestras eran muy porosas, no tenían resistencia mecánica, se desmenuzaban al rascarlas con la uña, el efecto era muy evidente en las mallas más gruesas 50 y 70.

El ensayo siguiente, aumentado la temperatura a 800°C, prácticamente no mejoró la calidad de las pastillas. Decidimos cambiar la atmósfera por otra mucho más protectora, usamos hidrógeno puro. Se cargaron en el horno las mismas mallas anteriores, la temperatura se fijó en 700°C y el tiempo una hora.

El resultado fue una mejora notable de la superficie, la cual se presenta limpia y casi brillante de color metálico rojizo, pero las probetas no tienen suficiente cohesión, se desgranan al rascarlas. En el ensayo siguiente elevamos la temperatura a 800°C, manteniendo las otras condiciones iguales. Resultado: las pastillas se contraen fuertemente en sus moldes, aproximadamente el 15% en volumen, se redujo el número de poros, su aspecto era limpio y metálico, tenían desde luego gran resistencia mecánica.

Todo ello es prueba de excesiva temperatura, un ensayo a 750°C nos dió poca cohesión, por lo tanto decidimos acortar el tiempo, manteniendo 800°C a media hora. El resultado fué excelente: buena cohesión, poca contracción (2 a 3%), superficie limpia y pulida. En un intento de bajar el costo y los riesgos del proceso cuando se usa hidrógeno, se nos ocurrió probar una atmósfera muy reductora formada por burbujeo de gas natural en alcohol metílico, se pueden ver detalles de la instalación en el diagrama adjunto (Fig. 2).

Repetimos las condiciones anteriores: cargamos las mallas 50, 70, 100 y 150, la temperatura fué de 800°C y el tiempo fué de media hora, usando la nueva atmósfera. Resultado: realmente extraordinario, con mejoramiento del brillo superficial. La idea ha sido objeto de una patente nacional tramitada con el número 183.356 el 28 de Agosto de 1963. Con este ensayo dimos por terminada la producción de pastillas y comenzamos a medir sus propiedades.

DETERMINACION DEL CAUDAL EN FUNCION DE LA PRESION

Con el dispositivo descrito anteriormente se midió, usando agua, el caudal que pasa a través de los filtros en función de la presión de e...rada, la presión de salida es la atmósférica. Es decir, manteniendo la presión de entrada constante se midieron los segundos que tarda en pasar un determinado volumen, eso a varias presiones de entrada y para cada filtro, tipificado por su malla. Los resultados de dichas mediciones se presentan en la Figura 6.

MEDICION DE LA PRESION DE ROTURA

Usando la técnica y el aparato antes descrito se realizaron una serie de ensayos hasta rotura, tres por cada filtro, correspondiente a cada malla. Con esos datos se calculó por unidad de área filtrante y por milímetro de espesor la resistencia específica para cada malla:

Malla	presión de rotura por cm2 y por mm. de espesor
50	60 atmósferas
70	70 "
100	85 "
150	88 "

OBSERVACION MICROSCOPICA

Se utilizó un microscopio metalográfico Leitz para fotomicrografía modelo Panphot, con accesorios para macrografía. Las placas eran de vidrio 9 x 12, procedencia nacional, marca Lasaf y tipo normal. Se comenzó por obtener fotomicrografías del polvo sin sinterizar, pero después de haber sido tamizado se tomaron las mallas extremas 50 y 150 y se procesaron juntas en la misma copia (Fig. 7).

Podemos observar con toda claridad el aspecto uniforme de cada partícula. La fotomicrografía de la Fig. 8 muestra las probetas tratadas a 800°C durante una hora, es decir un tratamiento excesivo; dichas probetas habían disminuido su volumen aproximadamente el 15% y con ello el número de poros.

Estas pastillas antes de ser observadas fueron pulidas con papeles esmeril de grano 100, 180, 400 y 600, y luego atacadas con ácido nítrico al 50%. Como ve

mos en la fotografía las partículas han dejado de ser esféricas para tomar formas poliédricas preferentemente de corte exagonal, tendiendo así a ocupar todo el espacio y eliminar los huecos y poros. La foto de la Figura 9 corresponde a una de las mejores muestras obtenidas a 800ºC, media hora y atmósfera gas-metanol. La probeta fué atacada y pulida igual que las anteriores. En ella se vé con toda claridad el proceso de sinterizado en el cuello de contacto de los granos, donde desaparece toda discontinuidad quedando las esferas metálicas soldadas, por difusión entre sí, dejando a sus lados poros de forma aproximadamente tetraédrica, cuyo corte da los triángulos negros de la foto.

La fotomicrografía de la Fig. 10 corresponde a dos filtros terminados, aumentados 6 veces correspondientes a las mallas 50 y 150.

CONCLUSIONES

Primera: Para la obtención de filtros de buenas propiedades debe partirse de polvos esferoidales como los obtenidos por soplado en estado líquido.

Segunda: No es necesaria ninguna presión de compactación ni en frío ni en caliente. Esto hace al proceso de muy bajo costo, pues solamente deben construir se matrices de chapa de hierro con la forma del filtro a obtener. La vida de las matrices es muy larga, pues no están sometidas a ningún esfuerzo mecánico ni ataque térmico u oxidación al ser calentadas en atmósfera protectora.

Tercera: La atmósfera protectora es muy simple, solo gas de la red de distribución domiciliaria añadido de metanol por burbujeo. Patente Argentina en trámite No. 183.356.

Cuarta: La capacidad filtrante es muy buena, para un filtro obtenido con polvo malla 50 (350 a 500 microns) que retiene partículas de 40 microns es capaz de filtrar un litro por minuto y por cm2 con una presión de entrada de solamente 0,5 atmósfera.

Quinta: Muy buena resistencia mecánica, el mismo filtro citado en la conclusión anterior es capaz de soportar una presión máxima de 300 atmósferas siendo su espesor de 5 mm y su diámetro de 20 mm.

Sexta: Además el filtro metálico posee las siguientes características: a) buena resistencia a la corrosión; b) resistencia a temperaturas elevadas, se pueden filtrar líquidos muy calientes; c) no son absorbentes; d) son de fácil limpieza (a contracorriente); e) se pueden fabricar con una gran uniformidad y en formas muy variadas y complejas; f) pueden ser mecanizados y soldados.

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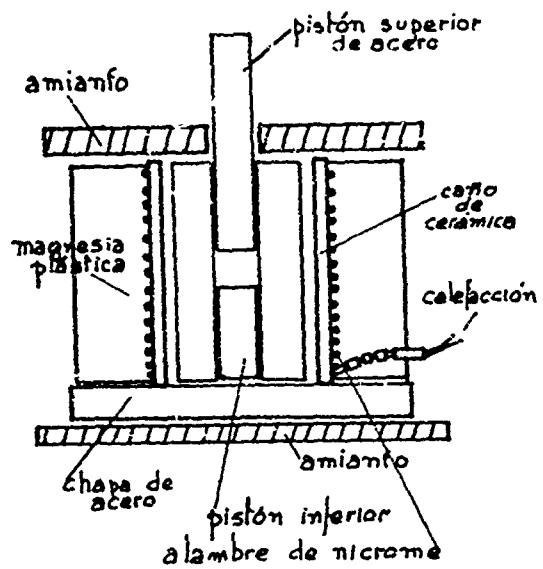
Fig. 1   Horno y Matriz de Sinterizado en Caliente
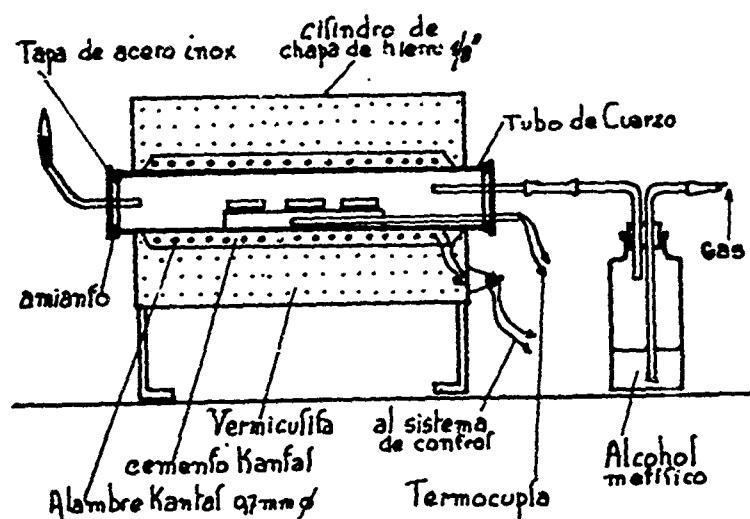
Fig. 2   Horno de Atmósfera Controlada
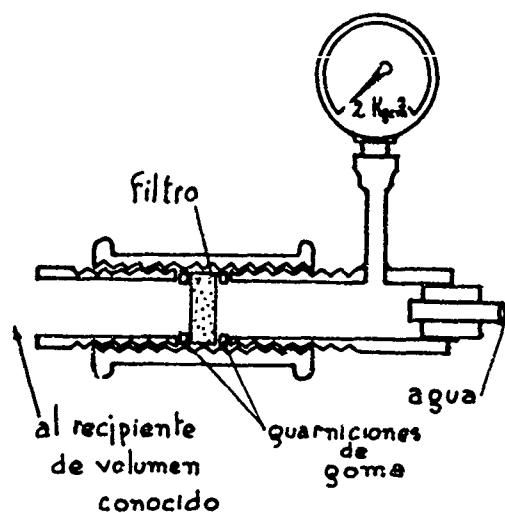
Fig. 3   Medidor del Caudal de Salida en Función de la Presión de Entrada
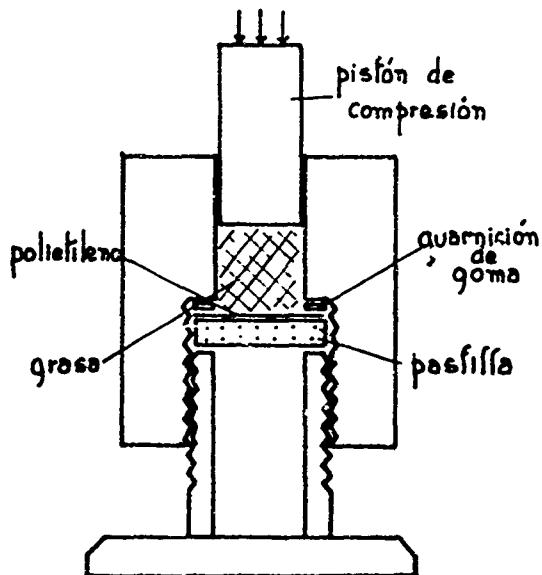
Fig. 4   Dispositivo de Medida de la Presión de Rotura
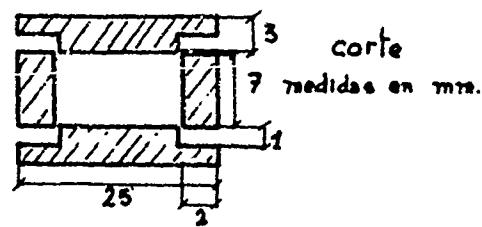
Fig. 5   Matriz para Sinterizado sin Compresión, sólo Calefacción
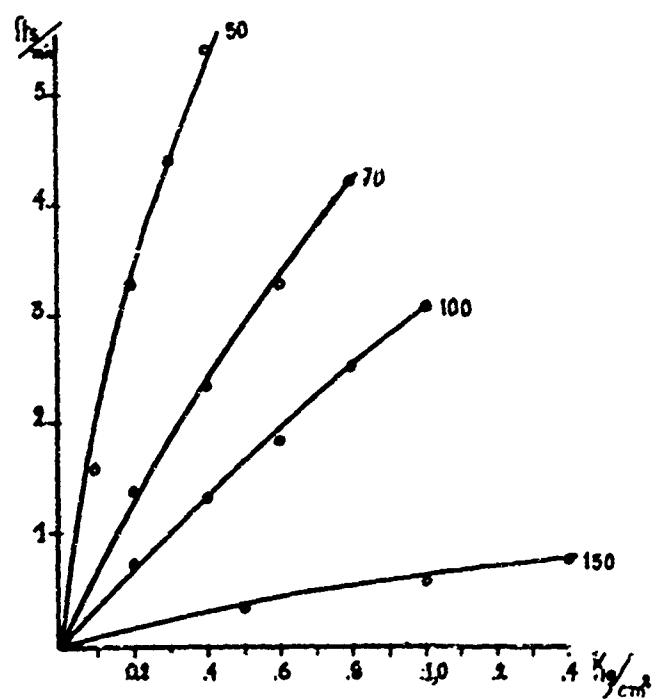
Fig. 6   Caudal de Salida en Función de la Presión de Entrada
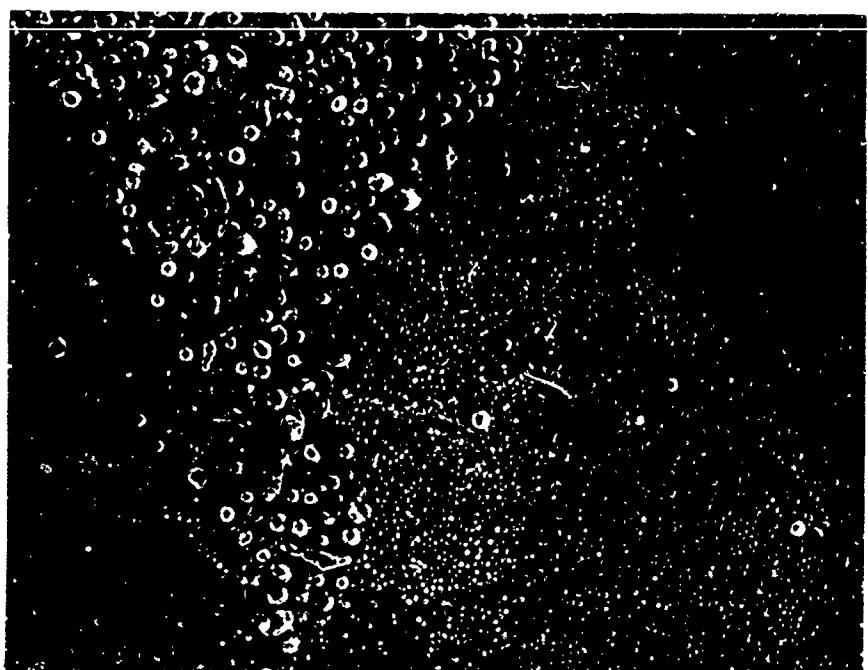
Figura 7   Determinación de Forma de Grano y Comparación de Polvo de Bronce
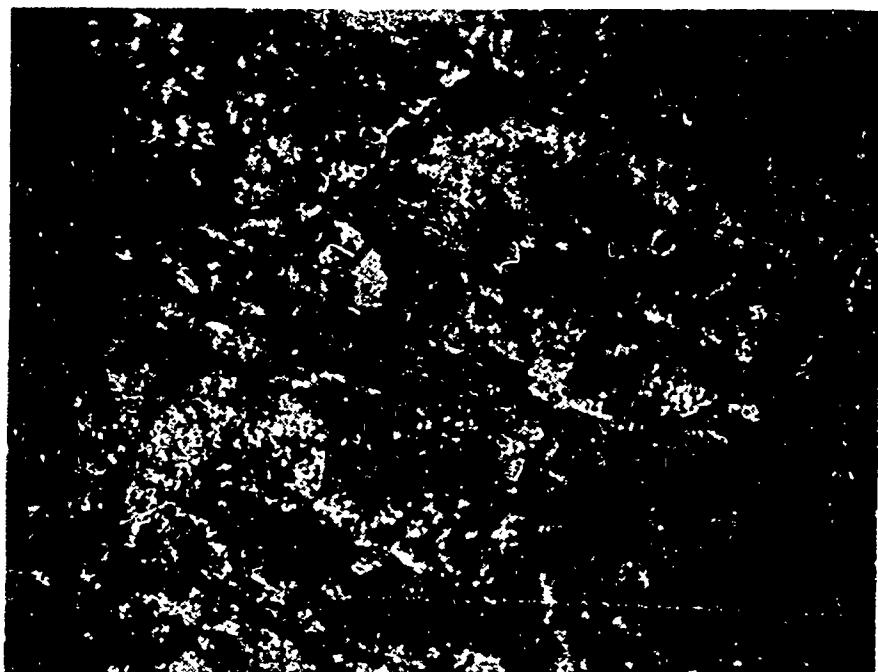
Figura 8   Determinación de Granos y Sinterizado en Filtros
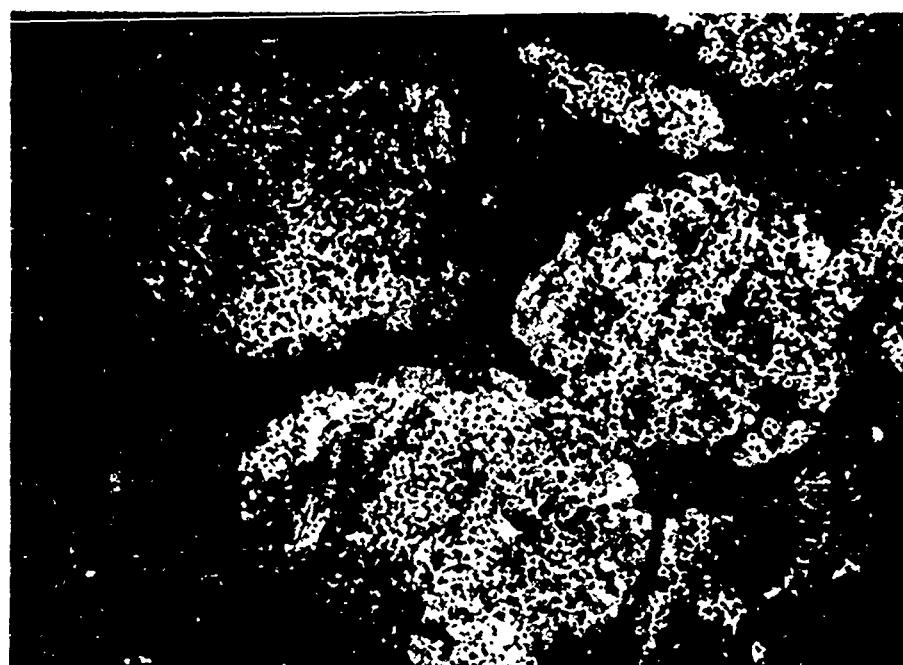
Figura 9   Determinación de Granos y Sinterizado en Filtros
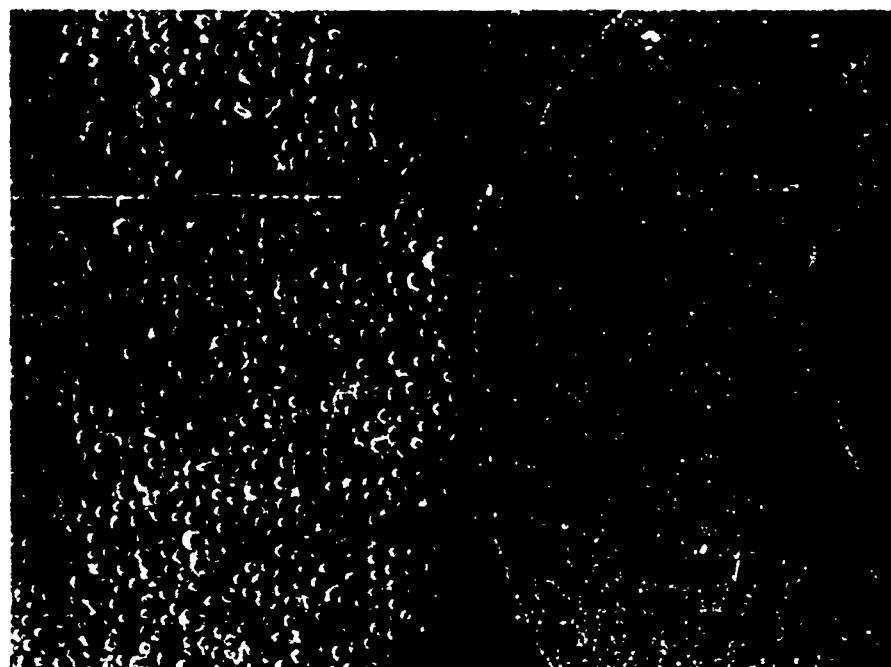
Figura 10   Determinación de Granos y Sinterizado en Filtros

NUEVA TEORIA PARA EL CALCULO DE ESFUERZOS EN LOS TRATAMIENTOS MECANICOS

por Eduardo R. Abril

Introducción

La aplicación de principios termodinámicos ha permitido, en muchos casos, resolver en forma clara y sencilla problemas tecnológicos cuya solución por otros medios era sumamente compleja.

Se considera que, siempre que sea posible aplicar criterios termodinámicos, las conclusiones a que se arribe serán rigurosamente ciertas, si las hipótesis iniciales lo son.

Independientemente de las objeciones de carácter lógico que pueda tener la aplicación en la solución de problemas prácticos, de leyes generales aceptadas "a priori", como lo son las termodinámicas, la verdad es que los resultados obtenidos hasta hoy dan a esas leyes una fuerza de convicción indiscutible en los campos en que han sido aplicadas.

Una de las ventajas innegables del método termodinámico es que permite prescindir de los detalles característicos de las transformaciones de los sistemas, y obtener conclusiones vinculadas exclusivamente con los estados inicial y final de dichos sistemas.

Este es el criterio que se utiliza en el presente trabajo, donde se encara la solución del problema de la determinación de potencias y esfuerzos en los procesos tecnológicos de deformación plástica, y por ello es posible decir que se ha aplicado un criterio termodinámico.

LA ENERGIA EN LOS SISTEMAS MECANICOS

Toda vez que se aplica un esfuerzo a un cuerpo sólido, se producen defor-

maciones en el mismo. Como consecuencia de ello, el cuerpo absorbe una cierta cantidad de energía que podrá quedar almacenada en el mismo o ser devuelta principalmente en forma de calor.

Cuando los esfuerzos aplicados son bastante elevados y los materiales tienen capacidad de deformación plástica, como sucede en los procesos que aquí se analizan, los cuerpos cambian de forma, y la cantidad de energía que el cuerpo retiene es sumamente pequeña en comparación con la que ha sido necesaria aplicar (aproximadamente el 10%).

El cambio de forma por deformación plástica es, pues, un problema de muy poco rendimiento termodinámico. A ello debe agregarse el hecho de que, para producir el cambio de forma es generalmente necesario consumir una gran cantidad de energía destinada a vencer los frotamientos que se originan por contacto entre el material y los dispositivos usados en la transformación.

La energía requerida por un proceso de deformación plástica, mediante el cual un cuerpo pasa de un estado a otro, puede calcularse si se conoce la variación, durante el proceso, de las tensiones existentes en cada punto del material, y además la ley que vincula dichas tensiones con las deformaciones unitarias que las acompañan.

En el estado actual, ese conocimiento es muy relativo y prácticamente desconocido en ciertos procesos, como el de estirado de alambres en hileras.

En vez de analizar la variación de tensiones y deformaciones que se producen durante el proceso, tal como se hace en la teoría clásica, se propone aquí la hipótesis de que la energía requerida para el cambio de forma por deformación plástica depende de los estados iniciales y finales del cuerpo, y no del modo en que se ha producido la deformación, siempre que en el proceso no se originen trabajos redundantes.

Aceptado este principio, y aclarado el concepto de trabajo redundante, es posible determinar, sobre nuevas bases, fórmulas para calcular la energía y los esfuerzos requeridos en procesos tecnológicos.

Antes de hablar del trabajo redundante y prescindiendo del mismo, se analizarán las razones que abonan la hipótesis de que el trabajo requerido para un cambio de forma es independiente del método usado para producir dicho cambio.

La principal razón es la idea de que la naturaleza trata siempre de ahorrar energía en sus transformaciones. Si un cambio de forma puede ser logrado de dos modos distintos, ambos continuos y progresivos, parece lógico que la naturaleza no tuviera interés en gastar más energía en un caso que en el otro, si los estados finales, en forma y propiedades, son iguales.

Como se observa que, a igualdad de temperatura, las propiedades físicas y

químicas de los materiales metálicos al final de los procesos tecnológicos dependen prácticamente del cambio de dimensiones (grado de reducción) y no de la manera en que dicho cambio se ha logrado, resulta lógico suponer que la energía absorbida por el cuerpo en ambos casos sea la misma. También resulta bastante lógico admitir, siempre prescindiendo del trabajo redundante, que la energía cedida en forma de calor al ambiente y por ende la energía total requerida sea la misma en ambos casos.

TRABAJO REDUNDANTE

El cambio experimentado por un cuerpo al pasar de un estado A a un estado B, de mayor nivel energético, exige siempre una energía mayor que la diferencia entre las energías que contiene el cuerpo en ambos estados.

Se supone en este estudio que existe un mínimo de energía adicional para que un material dado pueda pasar, por deformación plástica, de un estado de forma A a un estado de forma B, en igualdad de condiciones de temperatura y velocidad de deformación.

Sumando esa energía mínima adicional y la energía retenida en el cuerpo como consecuencia de la deformación, que se supone constante para un cambio de forma dado, se obtendrá lo que se designa como energía requerida para el cambio de forma. Si la energía utilizada en un proceso tecnológico es mayor que la requerida para el cambio de forma, se dice que el exceso corresponde a un trabajo redundante recibido por el cuerpo.

Un ejemplo aclarará este concepto de trabajo redundante. Si el cilindro de forma A de la Fig. 1 recibe un trabajo mecánico T para ser llevado a la forma B y otro trabajo igual para restituirlo a sus dimensiones iniciales como se muestra en C, diremos que el cuerpo ha recibido un trabajo redundante igual a 2T. Si el proceso continuara hasta que el cuerpo alcance la forma D, empleándose para ello un trabajo adicional T', la energía total recibida por el cuerpo en el proceso sería:

$$E = 2T + T'$$

El primer término del segundo miembro de esta expresión será considerado trabajo redundante en relación al proceso de pasar de A a D.

Se origina trabajo redundante siempre que exista fricción, y también cuando cambia el sentido de las fuerzas aplicadas, como sucede en muchas operaciones de forja.

Dado que en el ejemplo anterior el cambio de propiedades, y por consi-

guiente, de energía retenida, en los estados A y C puede llegar a tener cierta importancia, es lógico admitir que no todo el trabajo redundante es trabajo perdido con respecto a los estados iniciales y finales de un proceso, pero recordando que el trabajo retenido en los procesos tecnológicos es del orden del 10% del empleado, esas diferencias pueden considerarse despreciables y decir que el trabajo redundante se pierde siempre totalmente en forma de calor.

EL TRABAJO REDUNDANTE EN LA FRICCION

Consideremos el caso de estirado de un alambre a través de una hilera cónica. Si la superficie de ésta es teóricamente perfecta, no existirá frotamiento entre el material del alambre y el de la hilera, y el proceso de transformación se rá continuo y homogéneo mediante la progresiva disminución de área de cada sección transversal del alambre.

Por el contrario, si las superficies presentan rugosidades, cada sección transversal del alambre sufrirá variaciones no continuas de área. En efecto, dichas secciones en vez de disminuir progresivamente desde su entrada en la hilera hasta su salida, sufrirán, como consecuencia de las rugosidades de la hilera, aumentos parciales de área, tal como lo muestra exageradamente la Fig. 2.

En dicho ejemplo, el diámetro D_0 de un segmento de volumen ΔV disminuirá en forma continua hasta D'. En ese momento su valor como consecuencia de la rugosidad de la hilera, aumentará hasta D'' para disminuir luego el valor D' antes de continuar el proceso.

Cada vez que se produce, como consecuencia de la rugosidad de las paredes de la hilera, un paso tal como el de D' - D'' - D', se efectúa un trabajo redundante 2T, siendo T el trabajo relacionado con el paso de D' a D'' e igualmente el requerido para volver de D'' a D'.

ENERGIA REQUERIDA PARA EL CAMBIO DE FORMA EN EL ESTIRADO DE ALAMBRES EN HILERAS

Si bien la teoría que se desarrolla en este trabajo es aplicable a cualquier proceso tecnológico de deformación plástica, a continuación se tratará solamente el problema del estirado de alambres o barras en hileras ("trefilación"), dejándose para otra oportunidad la aplicación de los principios enunciados a otros procesos.

Si se plantea el problema de transformar por deformación plástica un cilindro metálico de sección A_0 y longitud L_0 en otro de sección A_1 y Longitud L_1, se admite en general que el volumen se mantendrá inalterable, es decir:

$$V = A_0 \ L_0 = A_1 \ L_1 \qquad (1)$$

De acuerdo con la hipótesis, antes establecida, de que la energía necesaria para el cambio de forma depende sólo de los estados iniciales y finales, podríamos calcular cual es el valor de esa energía suponiendo que hemos pasado del estado inicial al estado final, estirando el cilindro mediante un ensayo de tracción. El diagrama obtenido en dicho ensayo nos permitirá calcular el valor de la energía empleada en el proceso. Ese valor podrá luego utilizarse en relación a cualquier otro modo de producir el mismo cambio de forma.

El hecho de que, en un ensayo de tracción, los materiales metálicos de gran plasticidad sufran un fenómeno de inestabilidad llamado estricción, impide obtener reducciones de sección uniformes del orden de las obtenidas en los procesos tecnológicos. Sin embargo, ello no es un inconveniente para que podamos determinar con bastante exactitud el aspecto que presentaría el diagrama de tracción, si la estricción pudiera ser evitada y la sección transversal llevada al valor mínimo correspondiente al momento de la rotura en la zona de estricción (*)

La fig. 3 muestra un diagrama típico convencional de tracción y el aspecto que el mismo presentaría si la estricción pudiera ser evitada hasta el momento de la rotura.

Suponiendo que el ensayo se suspendiera cuando el cilindro de longitud L_0 alcance la longitud L_1, la distancia $L_1 - L_0$ determinará el alargamiento experimentado hasta ese momento, y la energía consumida en el cambio de forma será la correspondiente a la superficie del diagrama hasta la línea BC.

Si produjéramos el estiramiento del cilindro de longitud L_0 hasta el valor L_1 de otro modo, y también sin trabajo redundante, la energía absorbida sería la misma que la anterior, de acuerdo a lo ya expresado. El valor de esta energía puede ser calculado con bastante exactitud si se la asimila a la superficie del rectángulo OABC (**).

Dicha superficie W es igual a:

$$W = Pm \ (L_1 - L_0)$$

(*) Mediante ensayos de tracción en un medio bajo presión hidrostática puede ser evitada la estricción. También es posible imaginar un ensayo discontinuo en el que la probeta se vaya tomando cada vez en la zona estriccionada, para lograr una deformación prácticamente uniforme.

(**) Si se requiriese mayor exactitud, dicha superficie puede ser afectada de un coeficiente que resultará siempre muy próximo a la unidad, debido al gran valor de la deformación de rotura al eliminarse la estricción.

donde Pm es la carga máxima alcanzada en el ensayo. Como, por definición, la resistencia a la tracción de un material es igual a la carga máxima sobre la sección inicial, el valor de W puede expresarse así:

$$W = \sigma_o A_o (L_1 - L_o) \qquad (2)$$

donde σ_o es la resistencia a la tracción del material "antes de ser sometido al estiramiento".

Si quisiéramos conocer el valor de la energía requerida para producir el cambio de la forma del cilindro desde $A_o L_o$ hasta $A_1 L_1$ (sin frotamientos ni otros trabajos redundantes), por un proceso tecnológico tal como el de estirado en hileras, bastaría, pues, conocer el valor de la resistencia a la tracción del material y los cambios de forma experimentados en el proceso. Esto permite encarar el problema en forma más simple que la utilizada corrientemente.

CALCULO DE LA FUERZA TEORICA EN EL PROCESO DE ESTIRADO

En el proceso de estirado en hileras interesa, más que la potencia, la fuerza que es necesario aplicar para producir el estiramiento.

Es posible, de acuerdo con lo anterior, calcular fácilmente (siempre prescindiendo de los frotamientos) el valor de esa fuerza que llamaremos P_o.

Teniendo en cuenta que la energía W será igual a $P_o L_1$, podemos reemplazar en (2) y, realizando algunas transformaciones matemáticas basadas en la igualdad (1), llegar a la sencilla expresión:

$$P_o = \sigma_o (A_o - A_1) \qquad (3)$$

En el punto Verificaciones Experimentales se menciona una verificación experimental indirecta de esta fórmula.

LA FRICCION EN EL PROCESO DE ESTIRADO

Las fórmulas actualmente en uso para calcular el valor de P_o en el estirado en hileras, dan valores que en general no difieren mucho de los correspondientes a la fórmula (3), tratándose de reducciones corrientemente empleadas en la práctica.

Admitida una fórmula cualquiera para el valor P_o es posible calcular el va lor P de la fuerza total (incluídos los frotamientos), si se adopta un valor determi nado para el coeficiente de fricción μ . Así, utilizando la fórmula (3), dicho va lor resulta:

$$P = \sigma_o (A_o - A_1) (1 + \mu \, ctg \, \alpha)$$

(4)

donde α es el semiángulo de la hilera.

La gran cantidad de experiencias realizadas para verificar las fórmulas de cálculo de P llevan necesariamente a la conclusión de que, independientemente de los errores que puedan existir en la determinación de P_o, la influencia de la fric-ción en el proceso no puede ser la que establece la teoría clásica de la fricción, ya que las discrepancias encontradas entre la teoría y la práctica no pueden explicar-se simplemente en función del error que pueda existir en el cálculo de P_o. Todo sucede como si el valor μ variase grandemente en función de la geometría de la hi lera, y no solamente de la rugosidad de las paredes de la misma y la influencia del lubricante.

Se ha intentado dar al fenómeno de fricción, interpretaciones distintas a la clásica, con el fin de lograr una mejor concordancia con los valores experimenta-les, y en general se acepta que la teoría clásica de fricción no puede aplicarse sin correcciones al proceso de estirado en hileras.

Veiler y Lihtman (3) encaran el problema asimilando el coeficiente de fric-ción a una tensión de corte. Ello parece aplicable en los casos en que se utilizan lubricantes sólidos, pero inadecuado en otros casos.

La teoría que aquí se presenta, establece que la fricción absorbe energía solamente en función del trabajo redundante asociado al fenómeno, y que ese traba jo redundante depende de los cambios de forma que experimenta el material como consecuencia de la rugosidad de las superficies contra las cuales se produce el fe nómeno de fricción.

Lo explicado en relación a la fig. 2 aclara esta interpretación del fenóme-no de fricción. Se supone que si la hilera tuviera una rugosidad cero (imposible de alcanzar), el valor de P en la "trefilación" sería igual a P_o. La rugosidad de las paredes introduce un trabajo redundante que dependerá del grado de rugosidad de la superficie y de la efectividad del lubricante.

La acción del lubricante debe entenderse del modo siguiente: no existien-do lubricante, la barra al atravesar la hilera llenará íntegramente todas las rugo sidades de ésta produciendo aumentos y disminuciones de sección (a las que se asocia el trabajo redundante); existiendo lubricante, éste se alojará parcialmen te en las rugosidades, e impedirá el "llenado" total de las mismas por el metal, por lo cual el trabajo redundante disminuirá. El lubricante no puede escapar, a pesar de las grandes presiones ejercidas sobre él, debido al "sellado" que origi na el metal en los bordes de las depresiones (8).

En el caso de lubricantes sólidos la acción es equivalente, pero una energía adicional es requerida para vencer las tensiones de corte del material que sirve de lubricante. En este caso P puede disminuir por ser más efectivo el "llenado" de las rugosidades de la hilera, pero aumentar por el esfuerzo requerido en la deformación tangencial del lubricante.

CALCULO DEL ESFUERZO PARA VENCER LA FRICCION

Aceptado el criterio anterior respecto al fenómeno de fricción durante el estirado de alambre en hileras, es posible calcular el valor del incremento de esfuerzo requerido en el proceso, considerando que este incremento de esfuerzo corresponde a un trabajo redundante necesario para "llenar" las rugosidades y volver el material a las dimensiones que tendría si la hilera estuviera exenta totalmente de rugosidad.

A los fines de fijar conceptos, supongamos que fuese posible hacer que la hilera, en un momento determinado del proceso, elimine todas sus rugosidades, adquiriendo una superficie teóricamente lisa. Para ello deberíamos suponer una hilera hipotética con segmentos deslizantes sobre los que fuerzas F_1 F_2, etc., permitieran a voluntad crear o eliminar rugosidades (ver fig. 2). Partiendo de un estado dado de rugosidad, el tronco de cono alojado en la hilera habrá recibido un trabajo redundante T necesario para llenar las rugosidades; ahora bien, si incrementamos luego las fuerzas F_1, F_2, etc., hasta establecer el perfil teórico de la hilera, dichas fuerzas realizarán un trabajo que con gran aproximación podemos suponer igual a T.

El trabajo redundante asociado al material alojado en el tronco de cono será, pues, igual a $2T$ y dependerá de la profundidad media de las depresiones inicialmente existentes en la hilera.

Este trabajo adicional se realiza en la práctica incrementando el valor de la fuerza teórica con un valor ΔP que se admite como constante durante todo el proceso. Se tendrá entonces:

$$2T = d . \Delta P$$

donde d será la distancia recorrida por ΔP para ejecutar el trabajo 2T asociado al material contenido en el tronco de cono de la hilera.

El valor d será la longitud correspondiente a un cilindro de sección A_1 y volumen Vc igual al del tronco de cono de la hilera, es decir:

$$d = \frac{V_c}{A_1}$$

de donde resulta:

$$2T = \frac{\Delta P \, V_c}{A_1}$$

o sea:

$$\Delta P = \frac{2 \, T \, A_1}{V_c} \tag{5}$$

TRABAJO REDUNDANTE ADICIONAL EN EL ESTIRADO DE ALAMBRES

Aparte del trabajo redundante asociado a la fricción, existe, durante el estirado de alambres, otro trabajo redundante debido a un abultamiento del material que se produce a la entrada de la matriz, tal como lo indica la fig. 4.

Este trabajo puede llegar a ser muy importante y en algunos casos superar el correspondiente a la fricción.

Si bien los factores que afectan a uno y otro tipo de trabajo redundante son distintos, la rugosidad de las paredes de la hilera afecta a ambos por lo que, con el fin de desarrollar una fórmula de fácil aplicación, se hará una hipótesis simplificativa que permita analizar en conjunto ambos trabajos redundantes.

Si llamamos T' al trabajo redundante necesario para que el volumen Vc sufra el proceso de abultarse antes de entrar a la hilera y tenemos en cuenta que hace falta otro trabajo igual para eliminar dicho abultamiento, el trabajo redundante total (incluído el de fricción) será 2T + 2T' y la fórmula (5) se transformaría en:

$$\Delta P = \frac{2 \, (T + T') \, A_1}{V_c} \tag{6}$$

CALCULO DEL ESFUERZO DEBIDO AL TRABAJO REDUNDANTE

El valor T + T' de la fórmula (6) puede calcularse, y hallar así el valor Δ P, con las siguientes consideraciones simplificativas:

1. El trabajo redundante puede asimilarse al necesario para incrementar en una cantidad e los radios de las secciones transversales del material contenido en un momento determinado del proceso en el tronco de cono teórico de la hilera, y para volver después los radios a sus medidas iniciales.

2. El tronco de cono de la hilera puede ser asimilado a un cilindro del diámetro igual al diámetro medio de aquél.

3. El trabajo redundante total puede considerarse aplicado intermitentemente a volúmenes iguales a Vc.

El valor e, que debe adoptarse en el cálculo, será mucho mayor que la rugosidad media de la hilera, pues, por una parte, el abultamiento a la entrada de la hilera es de un orden muy superior a dicha rugosidad media, y por otra la acción del abultamiento y de la rugosidad se manifiesta en forma progresiva, y no intermitente. El carácter progresivo del proceso hace sufrir a cada volumen elemental V, una serie de variaciones de sección motivadas por las rugosidades, contrariamente a lo que sucede en el supuesto movimiento intermitente.

Con las consideraciones anteriores pasamos a determinar el valor T + T'.

Este trabajo redundante será considerado igual al necesario para que el material contenido en el tronco de cono de dimensiones teóricas tome las dimensiones de otro tronco de cono de igual volumen, pero con los radios de sus secciones transversales incrementados en la magnitud, o bien, lo que se supone equivalente para que el proceso se realice en sentido inverso (*).

Considerando cilindros de igual volumen y altura que los troncos de cono mencionados, con secciones transversales Am y A'm (según correspondan al tronco de cono primitivo c al incremento), las áreas de estas secciones corresponderán respectivamente a las áreas de las secciones medias de ambos troncos de cono.

Si llamamos respectivamente h y h' a las alturas de los cilindros considerados tendremos, debido a la constancia del volumen aceptada:

$$Vc = h' \, A'm = h \, Am \qquad\qquad (7)$$

De acuerdo a la fórmula (2) el trabajo necesario para pasar de un cilindro

(*) Las hipótesis simplificativas adoptadas aquí, equivalen a suponer que el trabajo redundante, requerido en el proceso de estirado, es igual al trabajo necesario para el cambio de forma de un cilindro de radio Rm+e a otro de radio Rm, siendo Rm el radio medio de la hilera y e una dimensión relacionada con la profundidad de las rugosidades y con el valor del abultamiento. En este caso el proceso sería continuo y no intermitente. Esto da otro método de deducción de la fórmula (9).

de sección A'm y longitud h' a otro de sección menor Am y longitud mayor h será igual a:

$$W = \sigma_0 \, A'm \, (h - h')$$

Este trabajo será igual a la mitad del trabajo redundante asociado al tronco de cono de la hilera o sea:

$$T \cdot T' = \sigma_0 \, A'm \, (h - h')$$

Teniendo en cuenta la constancia del volumen Vc esta fórmula puede escribirse como:

$$T \cdot T' = \sigma_0 \, (A'm - Am) \cdot h$$

Reemplazando el valor de h deducido de la fórmula (7) y llamando C al área de la corona circular determinada por A'm - Am se tendrá:

$$T \cdot T' \quad \frac{\sigma_0 \, C \, Vc}{Am}$$

Siendo e el espesor de la corona circular de área C, el valor de este área resulta con gran aproximación:

$$C = Dm \cdot e$$

De donde:

$$T \cdot T' = \frac{Dm \, e \, \sigma_0 \, Vc}{Am} \tag{8}$$

Reemplazando este valor de T - T' en fórmula (6) resulta:

$$\Delta P = \frac{2 \, Dm \, \sigma_0 \, e \, A_1}{Am}$$

Por transformaciones matemáticas se llega a:

$$\Delta P = 4 \sqrt{2 \pi} \cdot \frac{\sigma_0 \, e \, A_1}{\sqrt{A_0 = A_1}}$$

que con gran aproximación puede escribirse:

$$\Delta P = 10 \, e \, \frac{\sigma_0 \, A_1}{\sqrt{A_0 + A_1}} \tag{9}$$

CONSIDERACIONES ACERCA DEL FACTOR e

El factor e de la fórmula (9) desempeña un papel similar al que, en las fór mulas basadas en la teoría clásica de la fricción desempeña el coeficiente de fricción.

La dimensión de e es, sin embargo, el de una longitud, por lo que su valor depende del sistema de unidades lineales adoptado, a diferencia del valor μ que es adimensional.

El valor e depende, a la vez, de la profundidad de las rugosidades de hilera y de la magnitud lineal del abultamiento que se produce en el material a la entrada de una hilera. Ambos factores influyen en forma independiente en la determinación del trabajo redundante y ello introduciría un motivo de crítica a la fórmula (9).

Esto no obstante, la influencia de ambos factores puede ser representada por el coeficiente e de la fórmula (9) si suponemos que dicho valor es igual a la su ma de dos términos: e' correspondiente a la rugosidad y e'' correspondiente al abultamiento.

Para la determinación del valor de estos términos partimos de la hipótesis de que ambos varían proporcionalmente con el incremento de la rugosidad de la hi lera y que solamente el segundo término crece proporcionalmente con el aumento de las dimensiones lineales del tronco de cono de la hilera.

Por otra parte se supone que los restantes factores que intervienen en la magnitud del trabajo redundante influyen en forma equivalente en ambos términos, o cuando lo hacen en forma opuesta se autocompensan en las condiciones normalmente encontradas en la práctica.

En base a las experiencias analizadas en este trabajo, ha sido posible establecer que las suposiciones arriba mencionadas son correctas y que se puede asignar el siguiente valor para e:

$$e = e' + e'' = e' + e' \; (\sqrt{A_0 + A_1})$$

donde $\sqrt{A_0 + A_1}$ representa la influencia del aumento de dimensiones lineales del tronco de cono de la hilera en el término e''.

Con esta consideración podemos modificar la fórmula (9) de la siguiente manera:

$$\Delta P = 10 \, e' \, \sigma_0 \, A_1 \; \left(\frac{1}{\sqrt{A_0 + A_1}} + 1 \right)$$

Para simplificar esta fórmula, llamaremos f al producto 10 e' al que denominaremos "coeficiente de trabajo redundante".

De acuerdo con esto, la fórmula anterior puede expresarse:

$$\Delta P = \sigma_0 A_1 \left(\frac{1}{\sqrt{A_0 + A_1}} + 1 \right) f \qquad (10)$$

NUEVA FORMULA PARA EL CALCULO DE LA FUERZA DE ESTIRADO EN HILERAS

Sumando los esfuerzos correspondientes al cambio de forma y al trabajo redundante, se llega a la fórmula siguiente para el cálculo de la fuerza P requerida en los procesos de estirado:

$$P = P_0 + \Delta P = \sigma_0 (A_0 - A_1) + \sigma_0 A_1 \left(\frac{1}{\sqrt{A_0 + A_1}} + 1 \right) f \qquad (11)$$

La diferencia fundamental de esta fórmula con otras utilizadas es la presencia del valor correspondiente a la resistencia de tracción σ_0, y la ausencia del valor del ángulo de la hilera. El valor de P resulta así dependiendo de una característica muy conocida del material: su resistencia a la tracción y del grado de reducción que se quiere aplicar en el proceso, además de un coeficiente cuya determinación experimental resulta sencilla para condiciones dadas de rugosidad de las paredes de la hilera y para características conocidas del lubricante. Las variaciones de este factor, para diferentes condiciones de trabajo y diferentes materiales, se analiza en el punto Interpretación de los Resultados.

Dado que el esfuerzo requerido en el proceso depende de la resistencia a la tracción antes del estirado, se puede aplicar esta misma fórmula a procesos realizados a distintas temperaturas y velocidades de deformación. Sólo será necesario determinar en cada caso el valor de σ_0, del material a la temperatura y velocidad de deformación del proceso.

En las fórmulas clásicas las características del material figuran con un coeficiente relacionado con la resistencia del material en los estados inicial y final del mismo. Debido a que la resistencia después del proceso puede variar mucho, dicho coeficiente no puede adoptarse como constante, aunque muchas veces se lo tome así. El valor inicial de la resistencia a la tracción es, por el contrario, siempre constante para un material dado, en igualdad de condiciones.

INFLUENCIA DEL ANGULO DE LA HILERA

Para una misma reducción de área, todas las fórmulas hasta ahora utiliza
das expresan el valor de la fuerza de estirado en función de la magnitud del semi-
ángulo α del cono de la hilera.

Esa función no aparece expresada en la fórmula (11); ello podría hacer
pensar que las hipótesis simplificativas que llevaron a la deducción de dicha fór-
mula, no son aceptables.

Se estima sin embargo que la influencia del ángulo α sobre los coeficien-
tes relacionados con el abultamiento y la rugosidad son de carácter opuesto y se
autocompensan en la mayor parte de los casos encontrados en la práctica.

Las experiencias que se analizan más adelante, y que son interpretadas en
el punto Interpretación de los Resultados, permiten establecer que la mencionada
autocompensación es satisfactoria en la gran mayoría de los casos estudiados.

La figura 5, transcripta de un trabajo de Wistreich [1], y a la que se ha
agregado la curva representativa de la fórmula (11), muestra que si se trazaron
curvas correspondientes a los diversos ángulos utilizados, ellas se entrecruza-
rían, y que las diferencias entre los valores de Wistreich y los obtenidos con la
fórmula (11) están, en general, dentro de lo que podría considerarse errores ex
perimentales.

VERIFICACIONES EXPERIMENTALES

En el trabajo de S. Ya. Veler y V. I. Likhtman [3] figura una experiencia
que, realizada con otra finalidad, representa una verificación experimental de la
fórmula (3).

Mediante ensayos hechos en una hilera formada por rodillos libres de gi-
rar pudo determinarse el valor del esfuerzo de estirado sin fricción. Dichos au
tores trataron de encontrar una expresión para ese esfuerzo, con el fin de poder
calcular el valor del esfuerzo correspondiente a la fricción y establecer una teoría
sobre el mismo. Basándose en una fórmula primitiva de Sachs, que establece que
el valor de P_0 es igual a una cierta tensión vinculada con las características del
material, multiplicada por $(A_0 - A_1)$, ellos encontraron, experimentando con va-
rios materiales en distintas condiciones, que dicha tensión coincidía muy exacta-
mente con la resistencia a la tracción del material, por lo que adoptaron para el
esfuerzo de estirado sin fricción la expresión de nuestra fórmula (3).

Admitido como exacto el valor de P_0, se analiza -en las Tablas I a IX- una serie de experiencias ajenas, complementadas con experiencias propias (Tabla IX), destinadas a determinar el grado de exactitud de la fórmula (11).

El análisis realizado se refleja en las tablas mencionadas, en las cuales se ha determinado los valores teóricos de la fuerza de estirado y se los ha comparado con los valores experimentales.

La diferencia entre esos valores, expresada en porcentajes, figura en dichas tablas, como Δ %.

En las mencionadas tablas se han utilizado, además de los símbolos ya definidos, los siguientes:

f_p = Promedio del coeficiente de trabajo redundante.

ΔP_t = Fuerza debida al trabajo redundante calculada en base a f_p.

Δ = Diferencia en kg entre la fuerza total teórica y la experimental.

$r\%$ = Reducción de área, en por ciento.

Se ha puesto que, en cada experiencia, las condiciones de rugosidad de la hilera, y la efectividad de la lubricación han sido iguales y definidas por el valor de f_p, excepto para las experiencias de la Tabla VII, en las que se han utilizado dos tipos distintos de lubricantes.

INTERPRETACION DE LOS RESULTADOS

Los valores de f_p varían en las distintas experiencias entre 0, 04 y 0, 25.

Esta diferencia se considera perfectamente justificada si se tiene en cuenta que, como se puede ver en la Tabla VIII, el simple cambio de lubricante, sin modificar ningún otro factor, hace variar la fuerza de estirado en un 20%, y que ello representa una variación para f_p entre 0, 04 y 0, 09.

El valor $f_p = 0, 25$ de las experiencias que figuran en la Tabla V corresponde a ensayos hechos con un lubricante inadecuado para los procesos de estirado, y que se empleó en ese caso por necesitarse un lubricante que pudiera ser aplicado a presión, con el fin de verificar la influencia de ésta en el valor del esfuerzo de estirado.

Cuando los valores de Δ % de las tablas son menores del 10% se conside-

ra que los mismos están dentro del grado de exactitud con que pueden realizarse los experimentos. De los cuatro casos, sobre un total de 48, en los que el error resulta superior al 10%, solamente uno, el correspondiente al ensayo 15 de la Tabla I, parece estar apreciablemente influenciado por la exactitud de la fórmula (11). Esta, como consecuencia de haber supuesto nula la influencia del ángulo de la hilera, parecería que tiende a dar valores bajos para condiciones de reducción pequeña y ángulo grande, como los correspondientes a ese ensayo.

Es de hacer notar, sin embargo, que el error que se obtiene en ese caso con la fórmula (11), (37,5%) es sensiblemente inferior al que obtiene Whitton (62%) para el mismo caso, a pesar de haber utilizado éste las fórmulas clásicas corregidas con un término adicional, completamente empírico deducido precisamente en base a las experiencias de Wistreich.

Difícilmente se dan en la práctica de estirado en hileras condiciones de ángulo y reducción de área como las correspondientes al ensayo 15 de la Tabla I.

En los otros tres casos, en que el error resultante de aplicar la fórmula (11) excede del 10%, las diferencias son mucho menores que en el caso anterior, y dichas diferencias se pueden considerar afectadas fundamentalmente por factores experimentales. El pequeño diámetro de los alambres empleados en dichos casos, hace que la influencia de los factores experimentales pueda incidir notablemente en los resultados.

CONCLUSIONES

La fórmula (11), deducida por un procedimiento completamente distinto de los usuales, permite calcular con gran exactitud el valor de la fuerza requerida en los procesos de estirado en hileras.

La determinación del valor de f, para un tipo dado de lubricante y características también dadas de rugosidad superficial y geometría de la hilera puede hacerse simplemente en una máquina de ensayos de tracción, que es como se realizaron los ensayos de la Tabla IX.

Mediante ensayos de este tipo pueden compararse cuantitativamente los resultados obtenidos al introducir, en los procesos de estirado, modificaciones relacionadas con el tipo de lubricante empleado, forma de la hilera y acabado superficial de la misma.

Para aplicaciones prácticas con los lubricantes e hileras utilizados corrientemente, puede adoptarse con gran aproximación el valor 0,1 mm para el factor f.

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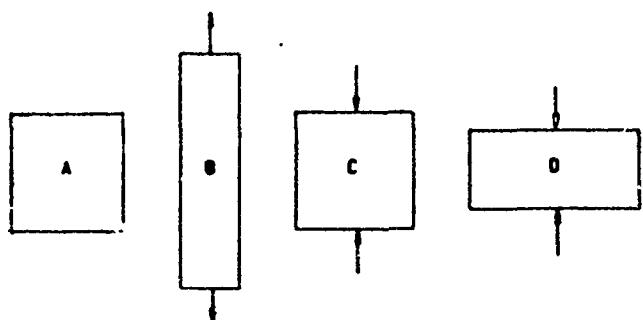
Figura 1   Trabajo Redundante en la Deformación Plástica
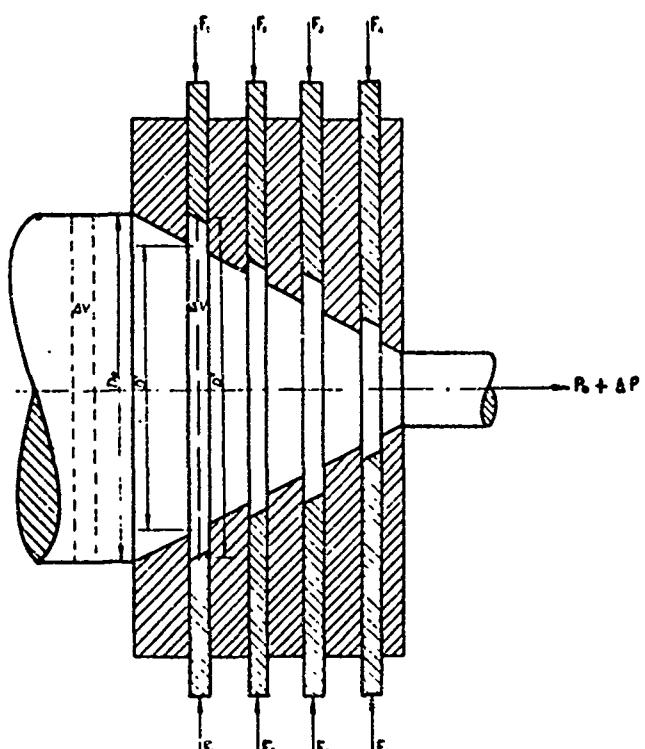
Figura 2   Trabajo Redundante en la Fricción
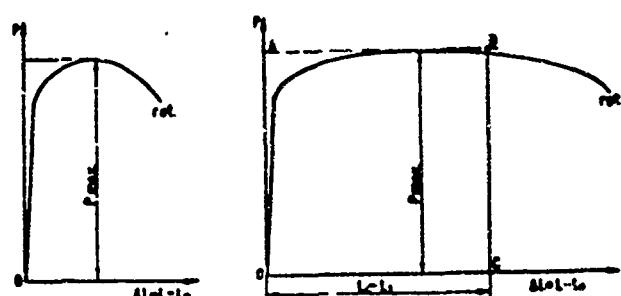
Figura 3   Diagramas de Tracción con y sin Estricción
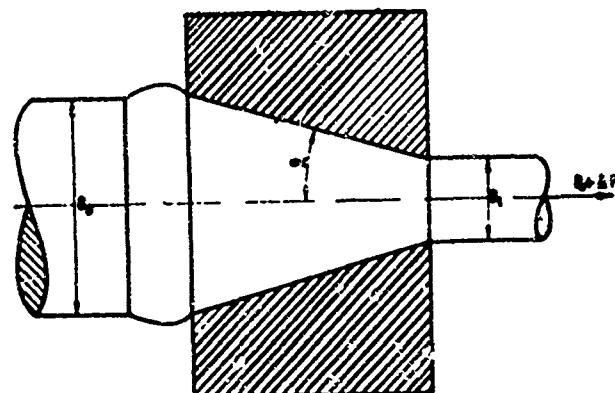
Figura 4　　　Trabajo Redundante por Abultamiento

	α radian
○	0·04
●	0·14
△	0·27
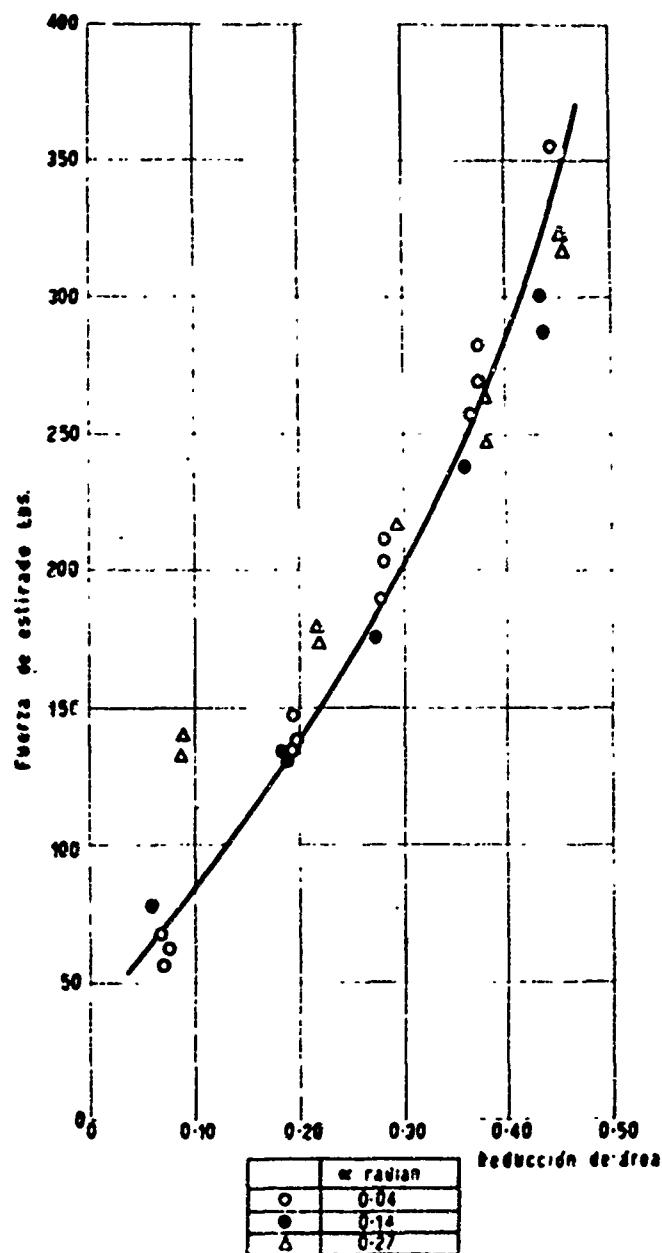
Figura 5　　　Experiencias de Wistreich Comparadas con la
Fórmula (11)

TABLA I

Referencias J. G. Wistreich[?]. — Material: cobre endurecido — Resistencia a la tracción: $\sigma_0 = 33$ kg/mm². — Lubricante: estearato de sodio. — Hileras acero de herramientas.

N.º	A₀ mm²	A₁ mm²	A₀−A₁ mm²	P₀ kg	P_comp kg	ΔP kg	ΔP/f kg/mm	f mm	f_p mm	ΔP₁ kg	Δ kg	Δ %	α grados	r %
1	9,20	5,06	4,14	136,5	155,0	18,5	210	0,088	0,09	18,9	+ 0,6	+ 0,4	2,29	45
2	8,03	»	2,97	98,1	120,0	21,9	213	0,103	»	19,2	— 2,7	— 2,2	»	37
3	7,26	»	2,20	73,0	94,5	21,5	214	0,100	»	19,3	— 2,2	— 2,6	»	30
4	6,35	»	1,29	42,6	63,8	21,2	215	0,098	»	19,4	— 1,8	— 2,9	»	20
5	5,62	»	0,56	18,5	36,0	17,5	217	0,080	»	19,5	+ 2,0	+ 5,5	»	10
6	9,20	»	4,14	136,5	146,0	9,5	210	0,045	»	18,9	+ 9,4	+ 6,4	8,00	45
7	8,03	»	2,97	98,1	107,0	8,9	213	0,042	»	19,2	+ 10,3	+ 9,6	»	37
8	7,26	»	2,20	73,0	88,0	15,0	214	0,070	»	19,3	+ 4,3	+ 4,9	»	30
9	6,35	»	1,29	42,6	64,1	21,5	215	0,100	»	19,4	— 2,1	— 3,3	»	20
10	5,62	»	0,56	18,5	41,5	23,0	217	0,105	»	19,5	— 3,5	— 8,4	»	10
11	9,20	»	4,14	136,5	146,0	10,0	210	0,048	»	18,9	+ 9,4	+ 6,4	15,50	45
12	8,03	»	2,97	98,1	113,0	14,9	213	0,070	»	19,2	+ 4,3	+ 3,8	»	37
13	7,26	»	2,20	73,0	94,0	21,0	214	0,098	»	19,3	— 1,7	— 1,8	»	30
14	6,35	»	1,29	42,6	75,0	33,0	215	0,153	»	19,4	— 13,0	— 17,3	»	20
15	5,62	»	0,56	18,5	60,8	42,3	217	0,190	»	19,5	— 22,8	— 37,5	»	10

TABLA II

Referencias: Francis and Thompson[?] (Tomado de P. W. Whitton[?]). — Material: cobre recocido — Resistencia a la tracción adoptada: $\sigma_0 = 31$ kg/mm². — Lubricante: jabón. — Hileras carburo de tungsteno sinterizado.

N.º	A₀ mm²	A₁ mm²	A₀−A₁ mm²	P₀ kg	P_comp kg	ΔP kg	ΔP/f kg/mm	f mm	f_p mm	ΔP₁ kg	Δ kg	Δ %	α grados	r %
1	2,60	1,69	0,91	28,2	31,7	3,5	77,1	0,05	0,064	4,9	+ 0,5	+ 1,6	12	34,9
2	»	»	»	»	31,7	3,5	»	0,05	»	»	+ 0,5	+ 1,6	10	»
3	»	»	»	»	31,7	3,5	»	0,05	»	»	+ 0,5	+ 1,6	8	»
4	»	»	»	»	31,4	3,2	»	0,04	»	»	+ 0,8	+ 2,6	6	»
5	»	»	»	»	38,0	9,6	»	0,13	»	»	— 4,9	— 12,9	4	»

TABLA III

Referencias: Francis and Thompson[?] (Tomado de P. W. Whitton[?]). — Material: latón 70:30 recocido — Resistencia a la tracción adoptada: $\sigma_0 = 31,5$ kg/mm². Lubricante: jabón. — Hileras carburo de tungsteno sinterizado.

N.º	A₀ mm²	A₁ mm²	A₀−A₁ mm²	P₀ kg	P_comp kg	ΔP kg	ΔP/f kg/mm	f mm	f_p mm	ΔP₁ kg	Δ kg	Δ %	α grados	r %
1	2,6	2,08	0,52	16,2	22,5	6,3	110	0,06	0,06	6,3	0	0	12	20
2	»	»	»	»	22,5	6,3	»	0,06	»	»	0	0	10	»
3	»	»	»	»	22,2	6,0	»	0,05	»	»	+ 0,3	+ 1,4	8	»
4	»	»	»	»	22,2	6,0	»	0,05	»	»	+ 0,3	+ 1,4	6	»
5	»	»	»	»	23,8	7,6	»	0,07	»	»	— 1,3	— 5,0	4	»

TABLA IV

Referencias: Baron and Thompson[?] (Tomado de P. W. Whitton[?]). — Material: latón 65:35 — Resistencia a la tracción adoptada: $\sigma_0 = 33$ kg/mm². — Lubricante: jabón. — Hileras carburo de tungsteno sinterizado.

N.º	A₀ mm²	A₁ mm²	A₀−A₁ mm²	P₀ kg	P_comp kg	ΔP kg	ΔP/f kg/mm	f mm	f_p mm	ΔP₁ kg	Δ kg	Δ %	α grados	r %
1	2,10	1,534	0,566	19,8	23,2	3,4	82,3	0,04	0,11	9,0	+ 5,6	+ 24,3	5,5	27,0
2	»	1,322	0,778	27,2	34,5	7,3	71,3	0,10	»	7,8	+ 0,5	+ 1,4	5,0	37,0
3	»	1,112	0,988	34,6	44,8	10,2	60,6	0,17	»	6,7	— 2,5	— 7,5	3,0	47,0
4	»	1,122	0,978	34,2	43,1	8,9	61,2	0,14	»	6,7	— 2,2	— 5,1	4,4	46,5
5	»	1,092	1,008	35,3	43,3	8,0	59,6	0,13	»	6,5	— 1,5	— 3,5	6,1	48,0
6	»	1,186	0,914	32,0	38,5	6,5	64,7	0,10	»	7,1	+ 0,9	+ 1,5	11,0	43,5

TABLA V

Referencia: V. F. Moseev y A. A. Korostelin[?]. — Material: acero St 10 — Resistencia a la tracción: $\sigma_u = 65$ kg/mm². — Lubricante: mezcla de aceite lubricante y kerosene.

N.°	A_0 mm²	A_1 mm²	A_0-A_1 mm²	P_0 kg	P_{sup} kg	ΔP kg	$\frac{\Delta P}{t}$ kg/mm	t mm	t_p mm	ΔP_1 kg	Δ kg	$\Delta\%$	α grados	$r\%$
1	2,00	1,64	0,36	23,4	65,0	41,6	162	0,26	0,25	40,6	—1,0	—1,5	12	17,8
2	»	1,495	0,505	32,8	70,0	37,2	149	0,25	»	37,2	0,0	0,0	»	25,4
3	»	1,30	0,70	45,5	77,0	31,5	131	0,24	»	32,8	+1,3	+1,7	»	35,0

TABLA VI

Referencia: Hoffman y Sachs[?]. — Material: acero para resortes — Resistencia a la tracción: $\sigma_0 = 100$ kg/mm². — Lubricante: compuesto especial. — Hileras: carburos sinterizados.

k.°	A_0 mm²	A_1 mm²	A_0-A_1 mm²	P_0 kg	P_{sup} kg	ΔP kg	$\frac{\Delta P}{t}$ kg/mm	t mm	t_p mm	ΔP_1 kg	Δ kg	$\Delta\%$	α grados	$r\%$
1	13	11,78	1,22	122	364	242	1412	0,172	0,19	268	+26	+7,1	5,6	16
2	»	10,52	2 48	248	495	247	1272	0,194	»	242	— 5	—0,1	»	19
3	»	9,35	3,65	365	620	255	1137	0,224	»	216	— 39	—8,4	»	28
4	»	8,32	4,68	468	667	199	1012	0,197	»	192	— 7	—0,1	»	36
5	»	7,28	5,72	572	724	152	888	0,172	»	169	+17	+7,4	»	44

TABLA VII

Referencia: Veiler y Likhtman[?]. — Material: cobre — Resistencia a la tracción: $\sigma_d = 35$ kg/mm². — Lubricante N.° 1: ácido oleico. — Lubricante N.° 3: solución al 5 % de oleato de sodio.

N.°	A_0 mm²	A_1 mm²	A_0-A_1 mm²	P_0 kg	P_{sup} kg	ΔP kg	$\frac{\Delta P}{t}$ kg/mm	t mm	α grados	$r\%$
1	63,8	50,3	13,5	462	639	177	1920	0,09	7,3	21
2	63,8	50,3	13,5	462	541	79	1920	0,04	7,3	21

TABLA VIII

Referencia: C. T. Yang[?]. — Material: aluminio — Resistencia a la tracción adoptada: $\sigma_0 = 10$ kg/mm². — Lubricante: albayalde y aceite de máquina.

N.°	A_0 mm²	A_1 mm²	A_0-A_1 mm²	P_0 kg	P_{sup} kg	ΔP kg	$\frac{\Delta P}{t}$ kg/mm	t mm	t_p mm	ΔP_1 kg	Δ kg	$\Delta\%$	α grados	$r\%$
1	26,82	25,70	1,12	11,2	43,9	32,7	292	0,112	0,105	30,7	—2,0	—4,6	10,1	4,07
2	28,00	»	2,30	23,0	58,3	35,3	»	0,121	»	»	—4,6	—7,9	»	8,11
3	30,18	»	4,48	44,8	74,9	30,1	»	0,106	»	»	+0,6	+0,8	»	14,06
4	31,65	»	5,95	59,5	82,4	22,9	»	0,079	»	»	+7,8	+9,4	»	18,82

TABLA IX

Referencia: experiencias propias hechas en una máquina universal de ensayos de 30 t. — Materiales: los indicados al pie de la tabla. — Lubricante: jabón común. — Hileras: acero de herramientas Rc 60. — Acabado superficial: 13 micro-inches.

N.°	A_0 mm²	A_1 mm²	A_0-A_1 mm²	P_0 kg	P_{sup} kg	ΔP kg	A_0+A_1 mm²	$\frac{\Delta P}{t}$ kg/mm	t mm	t_p mm	ΔP_1 kg	Δ kg	$\Delta\%$	α grados	$r\%$
1	284	241	43	1288	2000	712	525	7500	0,095	0,08	601	—111	—5,5	4	0,16
2	283	»	42	2815	4150	1345	524	16720	0,080	»	1345	0,0	0,0	»	»
3	281	»	40	2555	3620	1065	522	15880	0,066	»	1280	+215	+6,0	»	»

Material N.° 1: cobre recocido — $\sigma_0 = 30$ kg/mm². — Resistencia a la tracción después del proceso: 32 kg/mm².
Material N.° 2: acero de bajo carbono estirado en frío — $\sigma_0 = 67$ kg/mm². — Resistencia a la tracción después del proceso: 69 kg/mm².
Material N.° 3: acero para herramientas recocido — $\sigma_0 = 64$ kg/mm². — Resistencia a la tracción después del proceso: 75 kg/mm².

REFINACION A FUEGO Y OTRAS SOLUCIONES PARA LOS PROBLEMAS PRESENTADOS POR LA PRESENCIA DE IMPUREZAS EN COBRE Y LATONES ALFA

Por H. J. Destaillats, E. Gerarduzzi, R. A. Morando*

En nuestro país, las industrias de transformación de no-ferrosos, han su frido durante los últimos años el efecto de una fuerte presión competitiva. Por ello, para disminuir sus costos, han intensificado el uso de rezagos -muchas ve ces en forma inadecuada- y esto ha traído aparejados una serie de problemas de rivados de la impurificación de los productos obtenidos. Al mismo tiempo, el precio de los rezagos, sufrió una fuerte alza en relación al de los metales puros.

Así, el correcto aprovechamiento de una materia prima como el "scrap" de cobre, resulta un problema económico cuya solución sólo puede llegar por la vía técnica. Por eso algunas fábricas que no han seguido este camino se han en contrado fuera de competencia, por precio o por calidad.

Tratando de contribuir a solucionar este problema, que es de interés para el país en la medida en que puede significar un ahorro de importaciones y mejora de calidad, hemos trabajado sobre dos líneas relacionadas entre sí:

1. La puesta a punto de una técnica de refinación a fuego de cobre adaptada a las necesidades de fábricas transformadoras de tamaño medio.

2. El estudio, con miras a su aplicación industrial, de un método para eliminar el "hot shortness" producido por el plomo en cobre y latones.

A continuación pasamos a describir ambas técnicas.

* Departamento de Metalurgia. Comisión Nacional de Energía Atómica.

1. Refinación a Fuego de Cobre en una Instalación Indus-
   trial de Mediana Capacidad

De los dos caminos universalmente usados para la purificación del cobre
-electrólisis o refinación a fuego- hemos elegido este último por razones económicas.

Si bien es cierto que la electrólisis da directamente un producto de cali-
dad, su costo, unido al de las dos fundiciones necesarias para llegar a la forma
final a partir de retagos, la hacen antieconómica.

La refinación a fuego da en una sola operación el producto terminado y,
partiendo de scrap común, se puede obtener un producto cuya calidad resulta igual
a la del otro proceso.

Por otra parte, en la Argentina, el gran mercado del cobre se encuentra
en Buenos Aires, donde la energía eléctrica es cara y aún escasa.

Las principales impurezas que se presentan en el scrap de cobre, cuya
fuente más común son conductores eléctricos en desuso, son: Pb, Sn, Fe, Zn, Al,
Si, Ni.

De éstas, por sus efectos perjudiciales en el trabajado en caliente y por su
relativamente difícil eliminación en la refinación pirometalúrgica, el Pb resulta
el elemento más indeseable. Su presencia, sin embargo es muy común, originada
en recubrimientos de cables, piezas estañadas con Sn-Pb, y a veces en cables pro
tegidos con minio (Pb_3O_4) que se reduce fácilmente con materia orgánica de re-
vestimiento.

El Sn resulta también difícil de eliminar en comparación, por ejemplo,
con el Fe, Zn, P o Al y produce aumento de endurecimiento por trabajado, y no-
table disminución de la conductividad eléctrica.

La manera en que las distintas impurezas afectan las propiedades físicas
del cobre es bien conocida (1) y la mayor o menor facilidad relativa con que pue-
den eliminarse por oxidación está directamente relacionada con las energías libres
de formación de los óxidos respectivos (2)(Fig.1).

Previamente a la puesta a punto del proceso de fábrica se realizaron expe-
riencias en escala de planta piloto en el laboratorio de Metalurgia del SATI-CNEA.
En las mismas se estudió la introducción de variantes sobre el proceso clásico de
oxidación-reducción con miras a adaptarlo a la escala y los medios disponibles en
industrias de mediano tamaño.

Estas variantes son:

1.   el uso de cloro como agente purificador;

2.   la reducción con agentes gaseosos.

Describiremos su aplicación más adelante al hablar del proceso industrial.

Ensayos en planta piloto

Se modificó un horno del tipo volcador a crisol, de manera de poder utilizarlo como horno de "batea" a fuego directo. En las figs. 3 y 4 se ve un esquema del mismo. En la parte postero-inferior se lo proveyó de una tobera cuyo diseño se muestra en la fig. 5. La capacidad del horno así modificado es de 50 kgs.

La fusión de la carga se produce en la posición de la fig. 3, o sea con la tobera fuera del nivel del líquido. Para hacer burbujear aire o los otros gases usados en el proceso, se comienza el pasaje de los mismos en esa posición y luego se baja el horno hasta llegar a la posición de la fig. 4.

En este horno se ensayaron las etapas de refinación y también el comportamiento de los distintos refractarios. Se estudió la eliminación de impurezas usando scrap de distintos orígenes y también agregándolas como ligas madres. Así hemos obtenido, a partir de una materia prima con un contenido de 97% de Cu muestras que responden a la especificación ASTM para cobre tough pitch.

Toda la experiencia recogida en el trabajo en escala piloto fué trasladada a la puesta a punto en planta de un horno de refinación semi-rotativo de 1500 kgs de capacidad. En la fig. 6 se puede ver un esquema del horno usado. En la misma se pueden apreciar las 3 toberas agregadas, similares a la descripta antes.

La operación consta de las siguientes etapas que son las clásicas y bien conocidas:

1.   carga y fusión
2.   oxidación
3.   escoriado
4.   reducción a tough pitch (o desoxidación)
5.   colada

Además hemos introducido optativamente, antes o después de la reducción según el producto final deseado, una etapa de purificación por cloración.

Describiremos a continuación someramente cada una de estas etapas, deteniéndonos sobre los detalles novedosos o de mayor interés.

Fusión: Se conduce usando llama oxidante. Con esto se acorta bastante el período de oxidación posterior, ya que la incidencia directa de la llama contra el material aún no fundido tiene un efecto rápido. El combustible usado es diesel oil, de bajo contenido de azufre. En realidad esto es importante sólo después de la etapa de reducción, que es cuando el material puede absorber S.

Oxidación: Se inyecta aire a presión con las toberas en posición alta, y se gira el horno hasta obtener un fuerte burbujeo en el cobre.
Este sistema tiene muchas ventajas sobre el método de burbujear aire por medio de caños de hierro. Además de resultar más cómodo, ahorra el consumo de caños y elimina la posibilidad de contaminación por Fe. Una vez solucionados algunos inconvenientes constructivos iniciales no han habido problemas de obturación de toberas.
El proceso es seguido en la forma habitual, o sea, sacando muestras y observando las fracturas. El tiempo total en esta etapa es de alrededor de 1 hora, variando naturalmente con el tenor de impurezas presentes. Es necesario llegar a $0,6-0,7\%$ de oxígeno, valor con el cual prácticamente se tiene una buena eliminación de impurezas hacia la escoria.

Escoriado: Se usa arena seca para ayudar a retirar la escoria. Es muy importante que no quede escoria en el horno ya que en la etapa de reducción pueden reincorporarse impurezas que contiene aquella.

Cloración: Comparando los valores de las energías libres de formación de los compuestos clorados de los elementos presentes como impurezas con la del Cl_2Cu_2 (Fig. 2) se puede ver que la relación entre Cl_2Pb y la del Cl_2Cu_2 es más favorable que las correspondientes a los óxidos respectivos. De aquí se puede inferir que la cloración del baño fundido podría resultar un método más eficiente para la eliminación del plomo que la oxidación. Existe al respecto una publicación (3) en la cual el autor trabaja con valores más bien altos de elementos aleantes. Nosotros hemos aplicado el método -sólo y en combinación con la oxidación- para la eliminación de cantidades máximas de $0,5\%$ de Pb.

Además de la influencia de los valores termodinámicos citados, es importante hacer notar que el Cl_2Pb tiene un peso específico de $5,85$. Esto hace que el Cl_2Pb que se forma, flote y sea fácilmente eliminado del sistema, condición que

que no se dá con los óxidos de Pb cuyo peso específico oscila entre 8, 5 y 9 y cuya separación es más difícil por esta razón. En efecto, para que los óxidos sean eli minados es necesario que entren en contacto con la sílice de la escoria o, si se usa refractario ácido, de este último. Como el peso específico es similar al del Cu esta es una cuestión mecánica que generalmente debe ser resuelta por una agi tación muy efectiva.

En la práctica hemos comprobado que efectivamente, la reacción del Cl con el Pb se verifica rápidamente. En el gráfico de la fig. 7 se puede ver la dis minución del contenido de Pb en función del tiempo en un ensayo de cloración realizado sobre una carga sin oxidar. El valor final a que se llegó resultó me nor que 0, 005%.

Consideramos sin embargo que lo más conveniente es emplear la clora-ción como complemento de la oxidación, y no realizar toda la refinación a base de cloro debido a varias razones:

1.   al precio del Cl contra el del aire comprimido;

2.   al clorar siempre se forma Cl_2Cu y Cl_2Cu_2. Como estas sales son inso-lubles en el cobre fundido, pasan a la escoria formando una capa muy fluí da y volátil que ocasiona cierta pérdida de Cu. En vez, en el proceso de oxidación el óxido cuproso que se forma se disuelve en el cobre y es recu perado en la etapa de reducción;

3.   el efecto de eliminación de estaño por cloración (ver Fig. 7) es práctica-mente nulo y esto hace que de todas maneras sea necesario pasar por la etapa de oxidación cuando este elemento está presente;

4.   dado que siempre existen problemas toxicológicos con el uso del cloro, es preferible reducir su empleo a lo indispensable.

Cuando el producto final deseado es tough-pitch conviene hacer la cloración antes de reducir. La causa de ésto es que el cloro puede modificar el equilibrio Cu-H-O que rige la cantidad de vapor de agua formado en el momento de la solidifi cación y variar así el nivel característico del lingote colado horizontalmente.

Por el contrario, si se quiere terminar con Cu desoxidado con P, no hay in conveniente en clorar después de reducir, con la ventaja de eliminar de este modo las impurezas que pudieran reincorporarse a causa de un escoriado deficiente.

El problema del ataque de los materiales de construcción por el cloro fue solucionado usando un tubo de cuarzo en lugar de hierro en la tobera. Los meta-les son violentamente atacados por el cloro caliente y por lo tanto no pueden ser usados.

Reducción

Es conocida universalmente la utilización de palos verdes para reducir el contenido de oxígeno hasta el límite de 0,03 a 0,07% correspondiente al tough pitch. Sin embargo, existe actualmente una tendencia a usar agentes químicos reductores que permiten independizarse de los palos verdes cuyo empleo es muchas veces engorroso y aún antieconómico.

Por otra parte, en un horno relativamente chico como el que usamos, resulta muy difícil el empleo de madera para la reducción debido a que mientras están puestos los palos dentro del cobre no se puede encender el horno porque se quema la parte de aquellos que emerge.

Debido a la baja relación entre volumen y superficie con respecto a un horno grande, la inercia térmica es poca o sea, dicho en otras palabras, el horno se enfría demasiado rápidamente y no dá tiempo a completar la operación. Por el contrario, inyectando un reductor gaseoso por las toberas, se puede mantener al mismo tiempo el horno encendido y la temperatura no cae. Además resulta mucho más controlable la cantidad de material reductor que se inyecta, con lo que se disminuye el peligro de "pasarse" y también es más cómodo y limpio su empleo.

En 1962, S.S. Cole y L.W. Rowe describen la primera planta diseñada con éxito sobre esta base (4). En ella se emplea gas natural (metano) parcialmente oxidado como agente reductor. Prácticamente el gas usado resulta una mezcla de OC y H_2 como agentes activos, más un cierto porcentaje de N_2. El gas natural no es usado en su estado original debido a su inactividad química. Su oxidación catalítica se realiza en una instalación de funcionamiento contínuo que es descripta en el citado trabajo.

Nosotros,.. hemos usado una mezcla de alcohol metílico con gas natural o gas licuado, como vehículo. El dispositivo para su inyección es simple y puede verse en la fig. 8. Su costo es suficientemente bajo y puede adaptarse facilmente a una instalación del tipo usado aquí. Su manejo es también relativamente sencillo y sin peligros siempre que se tomen las precauciones elementales.

La operación de reducción se comienza pasando gas solo y luego bajando las toberas hasta la posición de burbujeo. Recién entonces se abre la entrada de metanol controlando su caudal con un rotómetro. Se sigue el proceso de la reducción sacando muestras del mismo tipo que las usadas para la oxidación y además botones que permiten observar el "set".

Hemos contrastado las probetas mediante una técnica rápida de metalografía, empleando el procedimiento de pulido químico, pero la conclusión es que el mejor método para decidir cuándo la operación está terminada sigue siendo el del ojo experto, usado en el cobre con éxito desde hace unos 40 siglos.

Pasamos ahora a la segunda parte de este trabajo. En la misma describi remos los estudios hechos hasta el momento sobre los:

2. Efectos del Agregado de Uranio en Latones Alfa conteniendo Pb

Es conocido el efecto del plomo en la pérdida de ductilidad del cobre y lato nes que son laminados en caliente. La misma es explicada por la insolubilidad del plomo que a la temperatura de trabajado del material forma una fase líquida la cual provoca la pérdida de cohesión entre los granos al ser sometidos a tensiones mecánicas.

En algunos casos este efecto puede ser eliminado o disminuído por adición de ciertos elementos. Los mecanismos por los cuales actúan estas condiciones no son siempre los mismos, y están aún en discusión. Por ejemplo, pequeñas cantidades de bismuto como 0,001% causan el mismo efecto que el plomo en cobre lami nado a temperaturas superiores a 270ºC. Pero a muy altas temperaturas de trabajado, se tolera una mayor cantidad de bismuto. Según (5) el agregado de fósforo tiene un efecto beneficioso en estos mismos casos y algunos atribuyen estas variaciones a un cambio en la tension superficial bismuto-cobre.

Otro caso parecido, descripto por Cottrell (6), es el de las adiciones de bismuto a latones conteniendo plomo. Segun este autor debido también a un cambio de la tensión superficial entre el plomo-bismuto y el material base se mejora la ductilidad en caliente.

R. Thomson y J. O. Edwards (7) han trabajado con uranio como elemento adi cionante, agregado en proporciones variadas con respecto al plomo. Así han conseguido eliminar el efecto de "hot shortness" en latones alfa. Según estos autores esto es explicado por la formación de un compuesto intermetálico uranio-plomo que tiene un punto de fusión más alto que la temperatura de trabajado.

Nuestro trabajo ha consistido en estudiar metalográficamente y en relación con su comportamiento mecánico, latones 70-30 con varios contenidos de plomo y uranio. Esto fué hecho con la intención de aclarar el mecanismo por el cual se pro duce el fenómeno y con miras a su posible aplicación industrial.

A continuación describiremos brevemente el procedimiento seguido para la obtención de las aleaciones ensayadas.

La fundición se realizó en un horno Tamman, en crisol de grafito y bajo at mósfera de argón. Se colocaron el latón y el plomo juntos y se llevaron a una tem

peratura de 1050ºC; luego se introdujo el uranio en forma de láminas delgadas, envueltas en hojas de cobre. Se mantuvo a 1050ºC durante 20 minutos agitando periódicamente y se coló en lingotera de hierro.

Los resultados obtenidos los podemos resumir de la siguiente manera:

1. Las muestras conteniendo hasta 0,3% de plomo pudieron ser laminadas en caliente sin dificultad, cuando se les agregó uranio en proporciones iguales y hasta triples del contenido de plomo (Fig. 11a, 11b). No así con contenidos menores de uranio que de plomo en cuyo caso se producen fisuras en las primeras reducciones (Fig. 11c).

2. Cuando se trabajó con 0,5% de plomo no fué posible evitar la pérdida de ductilidad, ni aún con agregados considerablemente mayores de uranio. Tampoco tuvo efecto alguno la variación de otros factores como el aumento del tiempo de contacto con el metal líquido.

Si bien la necesidad de una relación mínima uranio/plomo = 1 parece abonar la idea de la formación de un intermetálico, nosotros no hemos podido detectar metalográficamente el menor vestigio del mismo.

Por el contrario, las únicas fases que aparecen son las Cu_5U, de color celeste y ubicada interdendríticamente y el plomo, precipitado como placas de color oscuro. La primera resulta idéntica a la obtenida en una muestra con 3% de uranio pero libre de plomo, como puede verse en las micrografías de la fig. 9.

Además la distribución relativa de las fases Cu_5U y Pb es la misma en todas las probetas (Fig. 10) de modo que no se explica por qué razón el supuesto intermetálico dejaría de formarse al aumentar el contenido de plomo de 0,3 a 0,5%.

CONCLUSIONES

Aunque el estudio realizado no nos permite aún enunciar una teoría fundamentada al respecto, la ubicación de una fase Cu_5U en los límites de grano nos hace pensar que el efecto puede ser debido al desplazamiento del plomo de esa posición o bien al cambio de las tensiones interfaciales por formación de este compuesto. Ninguna de estas teorías explica sin embargo porqué con contenidos de 0 5% de plomo el fenómeno desaparece.

Creemos que este método puede llegar a ser una técnica interesante para ser utilizada industrialmente sobre todo como complemento de otras técnicas de refinación de cobre con altos contenidos de impurezas. La principal dificultad

que vemos para esta aplicación es que debido a la gran reactividad del uranio se producen pérdidas importantes de este elemento cuando se lo agrega en un crisol con material fundido al aire y por lo tanto serían necesarias técnicas especiales de fundición para su uso exitoso.

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FIG. 2 | FIG. 1

FIG. 3

FIG. 4

Refractario
de base grafítica

Caño
de
hierro
ò
cuarzo

Concreto
refractario
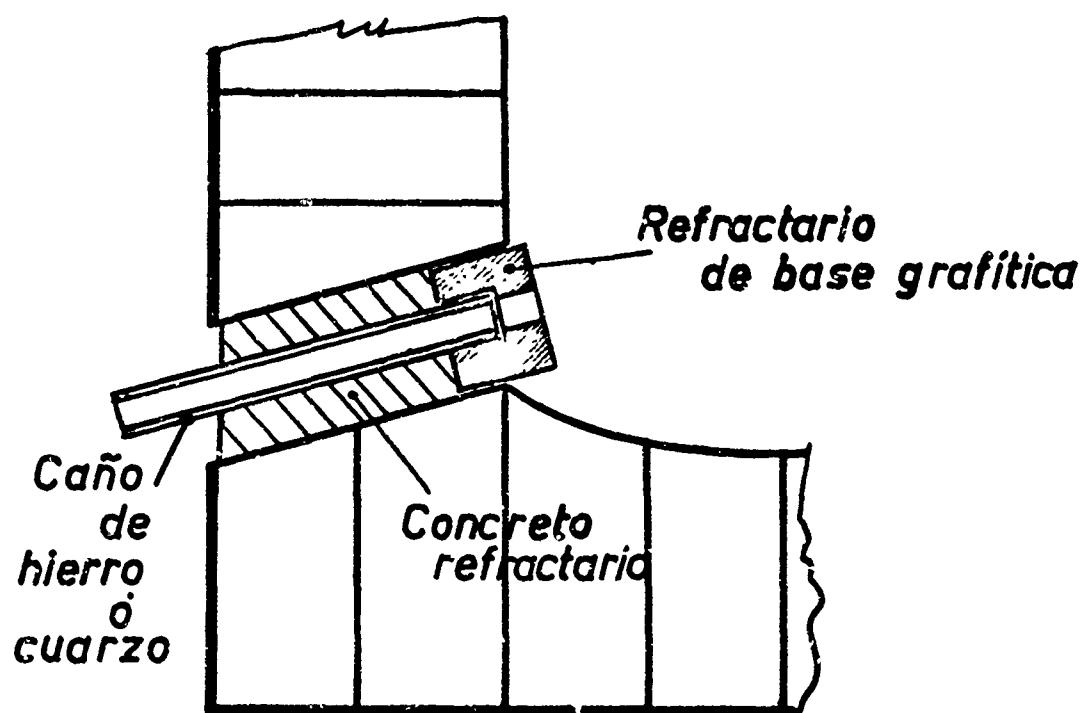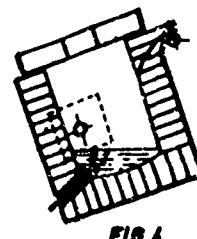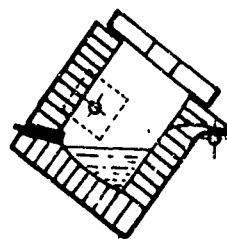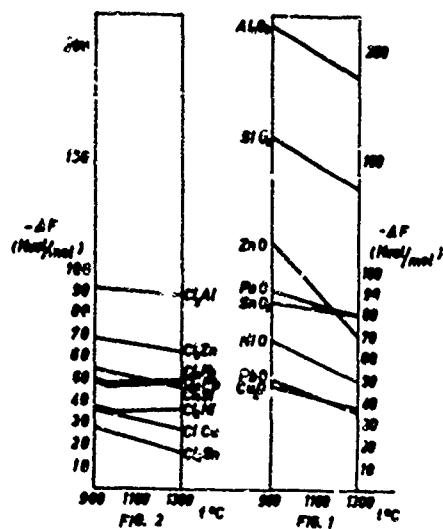
FIG. 5
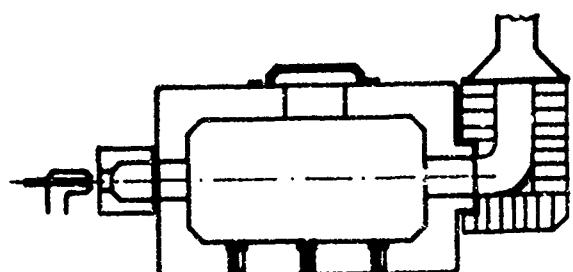
FIG. 6
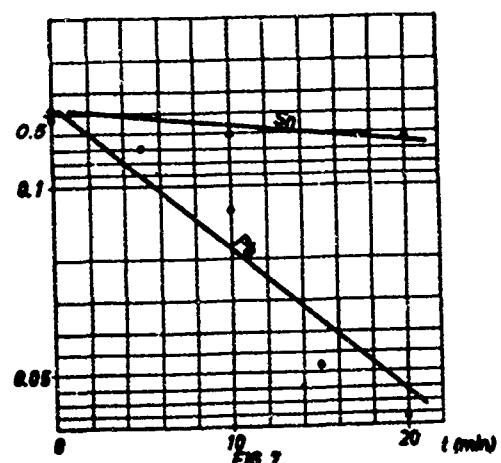
FIG. 7
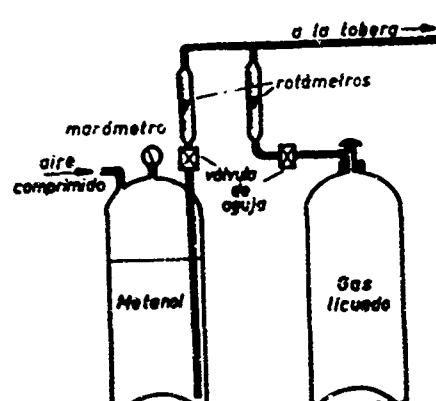
FIG. 8
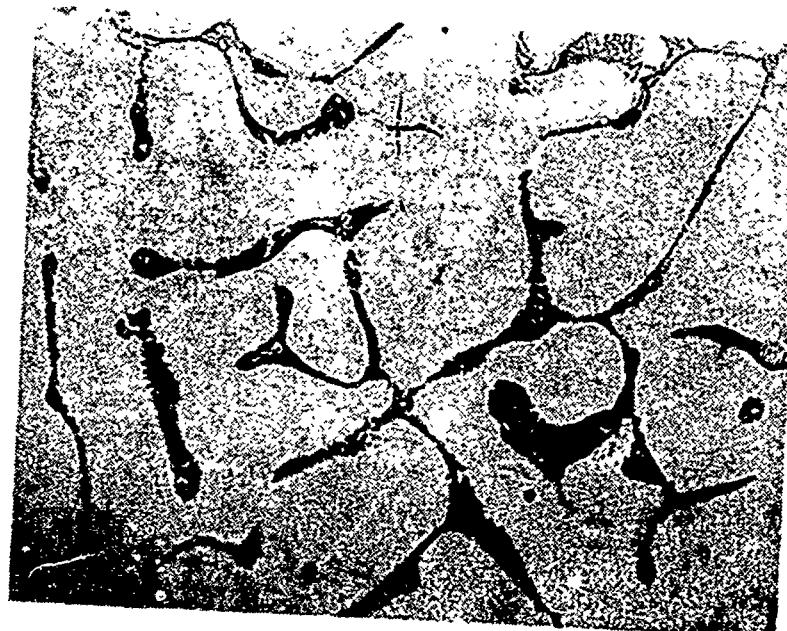
Fig. 9:   Cu U (3%)   800 x
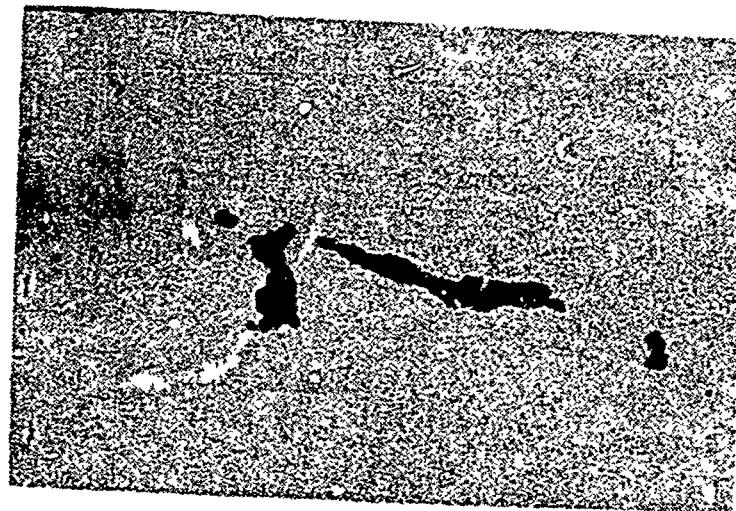
Fig. 10 :   Latón 70-30 - Pb 0,3%; U 0,9%   1000 x
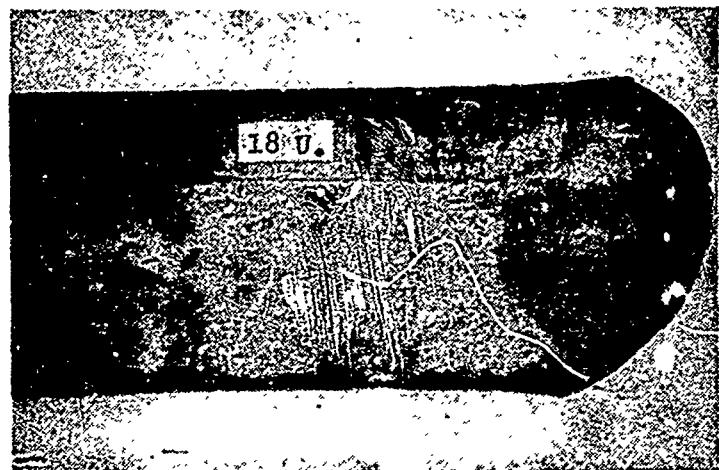
Fig. 11a :   Laton 70-30.   Pb 0,3%; U 0,9%
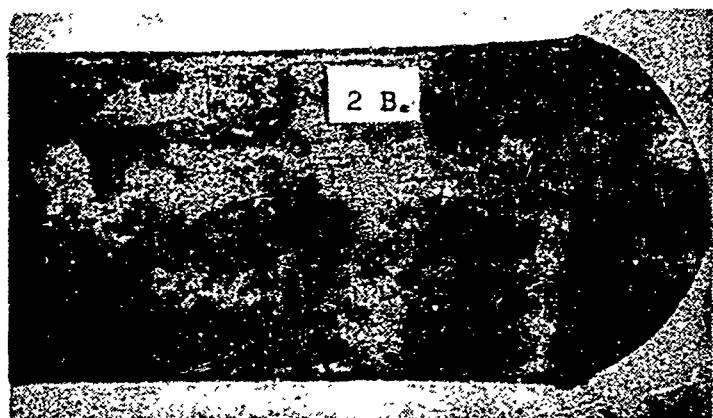
Fig. 11b :   Latón 70-30.   Pb 0,3%; U 0,3%
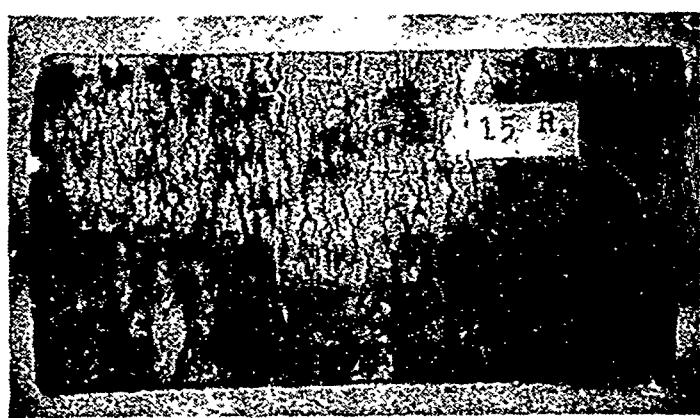
Fig. 11c   :   Latón 70-30 .   Pb 0,5%; U 1%

ESTUDO SÔBRE A DETERMINAÇÃO DE ALGUMAS CARACTERÍSTICAS RESIDUAIS DAS AREIAS DE MOLDAGEM

Quim. Victor Lo Ré (*)

RESUMO - O presente trabalho visa estudar a possi
bilidade de estabelecer um método de ensaio, que permita
a determinação de algumas características residuais nas
areias de moldagem, após seu contato com o metal líquido.
Estas determinações, efetuadas em corpos de prova padrão,
ajudam a esclarecer o comportamento da areia durante o
enchimento do molde. As características apresentadas pelas
areias, depois de submetidas a ação do metal líquido, pode-
rão servir de orientação para um melhor contrôle das adi-
ções de aglomerantes e aditivos às areias de moldagem. As
experiências nos levaram a concluir que o método é sucep-
tível a modificações embora demonstrasse a exequibilidade
do processo. O método permite estabelecer algumas corre
lações com resultados obtidos em outros tipos de ensaio.

1.   INTRODUÇÃO

Os ensaios das areias de moldagem, à alta temperatura, são normalmen-
te efetuados em laboratório, com o emprêgo do dilatômetro. Êste consiste essen

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(*) Responsável da Secção de Areias e Materiais de Moldagem do Instituto de Pes
quisas Tecnológicas; São Paulo, SP.

cialmente de u'a máquina de ensaio a compressão a quente, onde o corpo de prova e o dispositivo de transmissão de esfôrço ficam localizados em um forno aquecido elétricamente. A câmara do dilatômetro deve satisfazer às seguintes condições: temperatura uniforme e regulável e capacidade térmica para restabelecer a temperatura rápidamente depois de colocado o c.p. (fig.1).

Diversos trabalhos têm sido apresentados, modificando a técnica de ensaio a altas temperaturas, porém, sempre utilizando o dilatômetro como instrumento de medida (1). Consistiu em exceção um trabalho apresentado por Woodliff, "Mold surface behavior", sôbre a medida da expansão das areias, em que o corpo de prova de areia é envolvido pelo metal, e am medida é feita utilizando-se um defletômetro ligado por uma haste de quartzo apoiado no c.p. que transmitirá as variações da altura do c.p.(2). O ensaio assim realizado nos parece mais interessante comparado ao método do dilatômetro, pois que estando a areia em contacto direto com o metal, traduz resultados mais próximos do trabalho real na fundição. Diante destas observações, pareceu interessante tentar desenvolver um método que permitisse determinar algumas características residuais das areias de moldagem, após terem sido submetidas à ação do metal líquido.

Assim, foi estudada inicialmente a possibilidade de se determinar a resistência mecânica residual, a permeabilidade e a dureza superficial. O aparelhamento de medida consistiu em u'a máquina universal para ensaio de resistência de areias de moldagem, um permeâmetro e um medidor de dureza. Êstes aparelhos são fàcilmente encontrados em laboratórios de areia de fundição, ao contrário do dilatômetro que, pelo seu alto custo, sòmente pode ser adquirido por fundições de grande porte. Os corpos de prova utilizados foram preparados a partir de areia de composição conhecida, em medida padrão, e de acôrdo com métodos padronizados. Algumas caixas para conter os corpos de prova foram estudadas e utilizadas no decorrer dêste estudo. A maior dificuldade dêste trabalho consistiu no preparo de caixas adequadas para conter e submeter os corpos de prova ao contacto com o metal líquido, sem que os mesmos se danificassem ao serem retirados para ensaio.

Diversas tentativas foram feitas, alterando-se o tipo de caixa, e evoluindo para um sistema prático que eventualmente poderia vir a ser padronizado.

2. APARELHAMENTO E ENSAIO

Foram os seguintes os aparelhos utilizados para a realização do ensaio:

1.   Máquina Universal H.Dietert, empregada para a determinação de
resistência em c.p. úmidos, secos ou estufados. Consiste essen-
cialmente em um braço-mctor e pêndulo que giram em tôrno de
um eixo montado em base pesada, com suportes articulados para
receber o c.p.

2.   Permeâmetro ⁿieter. Consiste em um depósito cilíndrico com
água, no qual flutua, disposto telescópicamente, um tambor, em
borcado em água de modo a reter volume de ar superior a 2.000cm3
sob pressão estática de 10 g/cm2, tubulação de cêrca de 5mm de
diâmetro, e pondo em comunicaçao o ar com a cuba contendo mer
cúrio, onde é colocado o c.p. manômetro ligado a cuba de mercú-
rio com ábaco espiralado onde é feita a leitura direta da permeabi
lidade.

3.   Esclerômetro. Utilizado para determinar a dureza superficial em
c.p. sêcos. Penetrador em forma de faca.

Os métodos de ensaio e detalhes de aparelhamento são descritos nos méto
dos de ensaio M-32 a M-46 do IPT (3). Os corpos de prova foram preparados de
acôrdo com o método M-36 IPT, uas dimensões de 50,8 mm de altura por 50,8mm
de diâmetro.

3.   COMPOSIÇÃO DAS AREIAS ESTUDADAS

Os corpos de prova foram obtidos a partir de misturas dos seguintes ti-
pos de areia preparados de acôrdo com a técnica recomendada (4):

a) ·   Areia estufada para machos e moldes;

b)   Composição modificada de a);   e

c)   A mesma composição de a) com adição de serragem.

Nos casos b e c as modificações deliberadamente introduzidas foram no
sentido de verificar comparativamente a diminuição da resistência residual e
consequentemente a colapsibilidade. A areia a) é normalmente empregada para
a fundição de peças de ferro fundido comum, as areias tipo b) e c) são utilizadas

para ferro fundido de alto silício (Dur'ron).

Composição	a	b	c
Areia do mar (mod. 90-100) kg	100	100	100
Argila	4	4	4
Mogul	1,5	-	1,5
Dextrina	-	2	-
Oleo (oiticica)	2	1	2
Água	5	5	5
Serragem			1

Características	a	b	c
C.p. úmidos			
Umidade (%)	5	5	5
Permeabilidade (AFS)	40	45	46
Resistência a compresão (kg/cm2)	2,8	3,5	2,1
Dureza	60	55	45
Deformação (%)	3,0	3,5	3,0
C.p. sêcos - 220°C - 3h			
Resistência à compressão (kg/cm2)	19	19	19
Permeabilidade (AFS)	60	60	65
Dureza (AFS)	100	95	80

4. ENSAIO

Para a execução do ensaio, foram preparadas caixas de areia, nas medidas de 355 x 455 x 100 mm, nas quais foram montados os corpos de prova com separadores, também de areia. Os corpos de prova são envolvidos por 1 cm de (figs. 2-2a e 3).

Procedido o vazamento, após a caixa fria, desmolda-se cuidadosamente, retirando-se os corpos de prova que esto envolvidos pelo metal solidificado. Esta operação é facilitada pelos separadores de areia como poderá ser visto nas figs. 2 e 3.

Este tipo de montagem, entre anto, tem o inconveniente de obrigar ao vazamento individual de cada c.p. e ainda por setor isolado pelos separadores. Não fôra só o inconveniente da morosidade do processo, acresce ainda que as condições de vazamento podem se alterar para cada corpo de prova no que se refere a temperatura e velocidade de vazamento, dificultando assim uma padronização do

ensaio. Este tipo de caixa poderá eventualmente servir para serem observadas as reações metal-areia.

Resultados obtidos com o 1º tipo de caixa (fig.3):

1a. Série - Areia tipo a:

Temperatura inicial
de vazamento
1300º C

Permeabilidade (AFS)	50	60	50	45	48	60	50
Resistência à compressão (kg/cm2)		4,9	4,3	4,5	3,9	3,5	2,1
Dureza (AFS)	49	45	49	47	42	40	45

2º Série - Areia tipo a:
Temperatura inicial
de vazamento
1280º C

Permeabilidade (AFS)	67	65	62	55	
Resistência à compressão (kg/cm2)		4,5	3,1	4,2	3,5	2,2
Dureza (AFS)	49	45	49	42	40

3a. Série - Areia tipo b:
Temperatura inicial
de vazamento
1290º C

Permeabilidade (AFS)	63	65	45	50	45	30
Resistência à compressão (kg/cm2)		8,4	3,5	4,9	2,2	2,1	2,5
Dureza (AFS)	50	52	49	49	45	40

No sentido de corrigir as deficiências do processo anterior, várias caixas foram estudadas, evoluindo para a confecção de uma placa com canal central de alimentação, permitindo desta forma o vazamento simultaneo de seis c.p., e reproduzindo aproximadamente o trabalho de uma areia em uma caixa de fundição. Inicialmente foi usado o modêlo da fig. 4, modificado conforme pode ser visto na

fig.5, na parte referente aos canais, visando desta forma a retirada mais fácil dos c.p. Nêstes dois últimos processos o vazamento é feito em caixa fechada, ao contrário do primeiro que era em caixa aberta. O número de separadores foi reduzido a 2.

Resultados obtidos com o 2º tipo de caixa (fig.4):

1a. Série - Areis tipo a:

Temperatura inicial
de vazamento
1300º C

Permeabilidade (AFS)	50	50	48	49	52
Resistência à compressão (kg/cm2)	3,5	4,2	4,8	4,7	4,5
Dureza (AFS)	60	65	64	62	59

2a. Série - Areia tipo b:

Temperatura inicial
de vazamento
1300º C

Permeabilidade (AFS)	-	-	-	-	-
Resistência à compressão (kg/cm2)	2,1	2,2			
Dureza (AFS)	40	50	45		

Resultados obtidos com o 3º tipo de caixa (fig.5):

1a. Série - Areia tipo a:

Temperatura inicial
de vazamento
1280º C

Permeabilidade (AFS)	45	48	50	45
Resistência à compressão (kg/cm2)	4,2	3,6	4,1	
Dureza (AFS)	35	45	45	35

2a. Série Areia tipo c:

Temperatura inicial
de vazamento
1280º C

Permeabilidade (AFS)	–	–	–	–	–
Resistência a compressão (kg/cm2)	2,1	1,9	1,7		
Dureza (AFS)	40	30	40		

Areia tipo b (não foi possível a determinação)

Nêstes dois últimos tipos de caixa, a retirada dos corpos de prova de areia de baixa resistência (b e c) foi muito difícil. Para c.p. de resistência abaixo de 3 kg/cm2, é aconselhável o 1º tipo de caixa (caixa aberta), pois os três separadores de areia permitem a retirada dos espécimes mais facilmente, sem danificá-los.

Um nôvo estudo dos projetos das caix... tipo 4 e 5, com a montagem de 3 separadores de areia, deverá permitir a fácil retirada dos c.p., com a vantagem do vazamento uniforme.

Como primeiro estudo foi tentada uma nova forma de alimentação vista nas figs. 6, 7 e 8.

Resultados obtidos com o 6º tipo de caixa:

Areia tipo a:

Temperatura inicial
de vazamento
1300º C

Permeabilidade (AFS)	70	68	68	68
Resistência à compressão (kg/cm2)	6,3	6,5	6,3	6,2
Dureza (AFS)	70	80	80	70

Areia tipo b:

Temperatura inicial
de vazamento
1300º C

Permeabilidade (AFS)	50	48
Resistência à compressão		
(kg/cm2)	2,8	3,0
Dureza (AFS)	45	45

A desmoldagem dos corpos de prova processou-se sem dificuldade, permitindo a retirada dos mesmos sem danificá-los. Como apenas uma experiência foi efetuada, os resultados deverão ser confirmados em mais alguns vazamentos. Na fig. 9 podemos observar o último tipo de placa utilizada para o preparo de caixas. Note-se os quatro separadores de areia visando facilitar a retirada dos corpos de prova.

Menos do que a obtenção de resultados precisos, em grande número, o objetivo principal dêste trabalho foi verificar a exequibilidade do ensaio através do estudo das caixas para conter os corpos de prova e a possibilidade de se obter resultados reprodutíveis para c.p. nas mesmas condições de vazamento.

5. CONCLUSÕES

1. A tentativa para estabelecer um método inédito de ensaio é suscetível de modificações, sendo necessário prosseguir os estudos.

2. Será conselhável o estudo do efeito da aplicação de carga de compressão nos corpos de prova submetidos ao contato direto com o metal líquido, no momento do vazamento.

3. Os valores obtidos para a resistência residual permitem estabelecer uma correlação com a colapsibilidade no caso das areias para macho.

4. O conhecimento das características residuais de uma areia de mol dagem permite um melhor contrôle na adiçao de aglomerantes e aditivos visando efeitos especiais, inclusive na aplicação de pinturas.

5. Os resultados obtidos permitirão, em estudo futuro, estabelecer comparação com outros resultados obtidos em ensaios de alta tem peratura realizados com o dilatômetro.

6. Dos estudos realizados poderão resultar tipos de ensaios, permitindo a observação da areia após seu efetivo, uso, de forma mais evidente do que os ensaios efetuados no dilatômetro.

7. Os resultados obtidos autorizam a afirmar que o campo fica aberto ao estudo de inúmeras composições de areia, onde argilas e outros aditivos podem ser analisados em face da resistência residual, cor relacionando o seu comportamento com a colapsibilidade.

8. As reações metal-areia poderão vir a ser estudadas pelo método descrito.

9. O método estudado é econômico, prático, e pode ser usado na ma· ria das fundições.

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AGRADECIMENTO
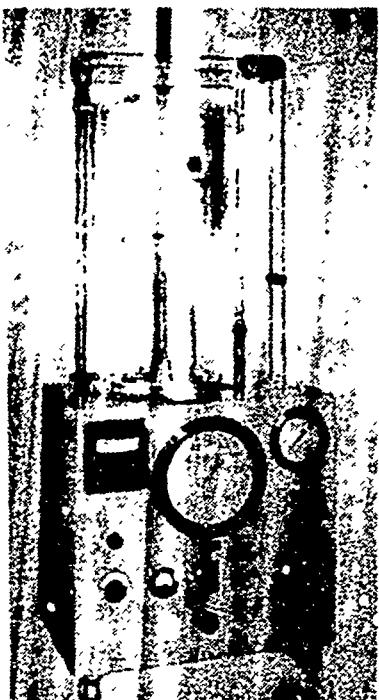
Fig. 1   Aspecto d˙ dilatometro para ensaio de areias de moldagem a altas
temperaturas.   Consiste essencialmente num dispositivo de
compressao a quente; o corpo de prova fica localizado no forno
superior, aquecido eletricamente.
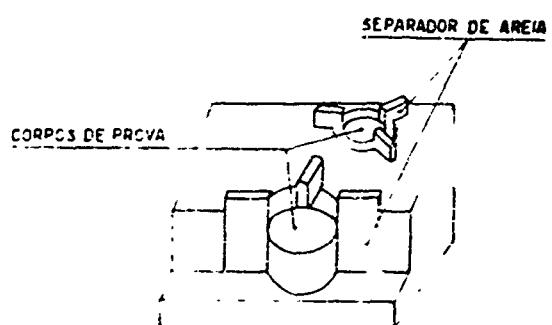
Fig. 2   Caixa de areia individual para ensaio do corpo de prova de areia de
moldagem; veem se os separadores de areia

Aspecto fotográfico de caixa de madeira da figura anterior. os corpos.
à prov. são envolvidos por uma camada de m. al tr. ado de 1 cm
de espessura
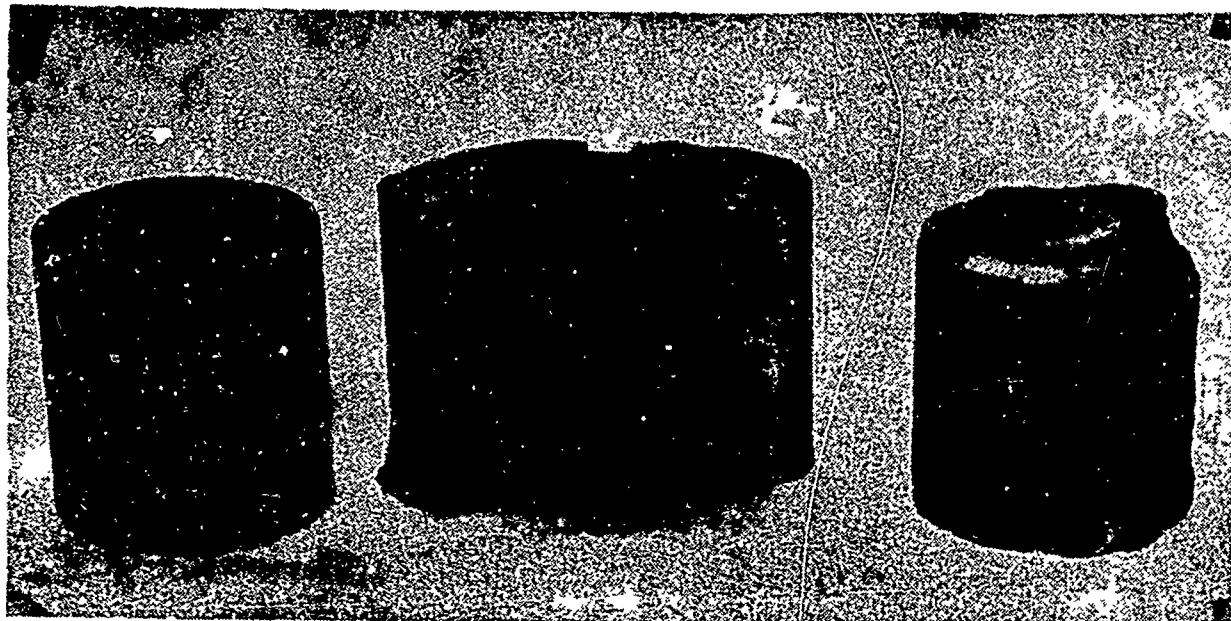
Fig. 3   Aspectos dos corpos de prova da experiencia da figura anterior
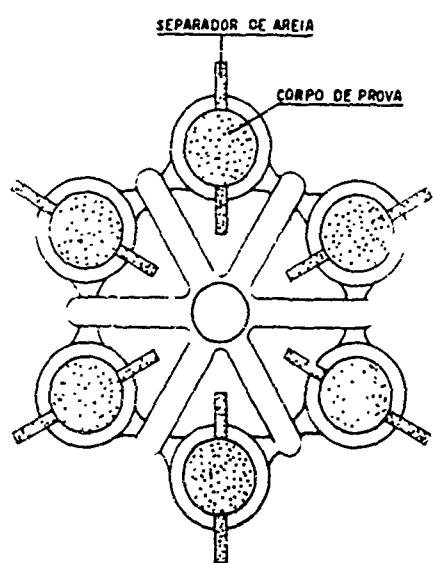
Fig. 4   A caixa das figuras 2 e 3 evoluiu para uma placa com canal central
de alimentaçao; permite o vazamento simultaneo de 6 corpos de
prova e se aproxima mais de uma fundiçao real
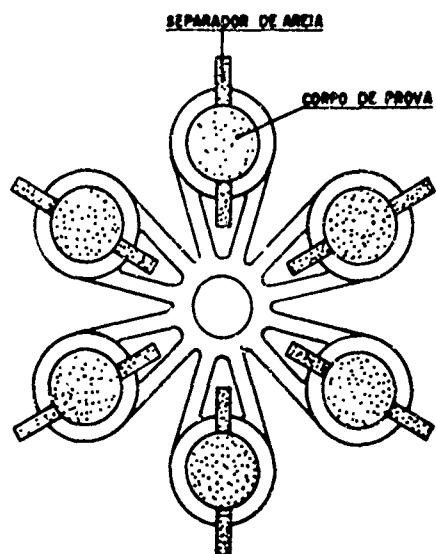
Fig. 5   A placa da figura anterior foi melhorada na parte referente aos
           canais; visando a retirada mais fácil dos corpos de prova
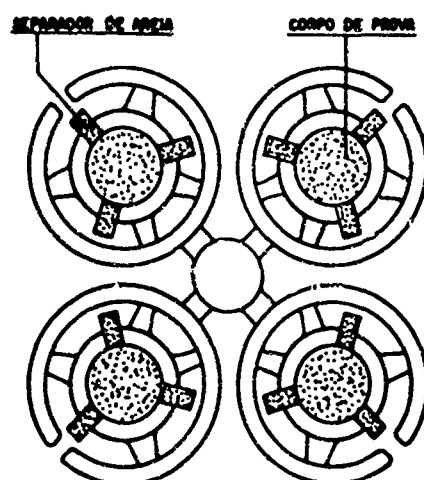
Fig. 6   Nova forma de alimentaçao foi tentada; a desmoldagem dos corpos
           de prova processou-se sem dificuldade. Os ensaios prosseguem
           com esta nova caixa
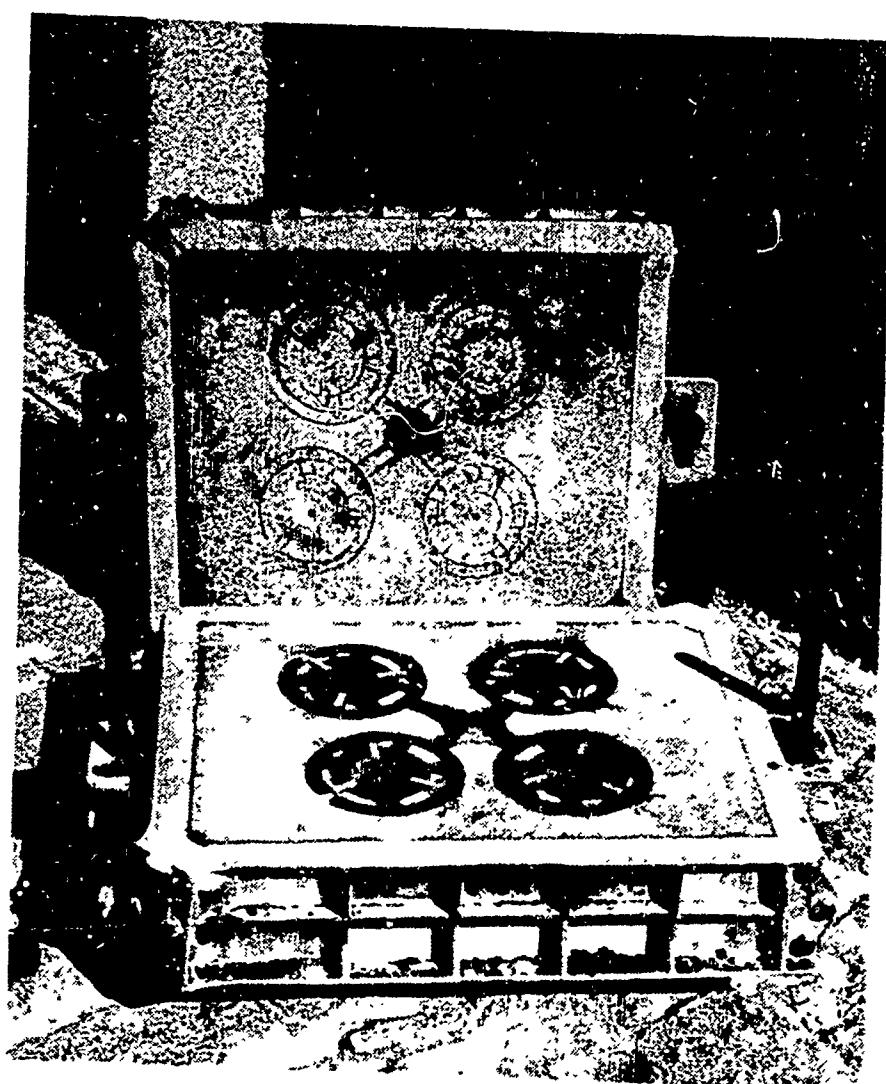
Fig. 7   Vista fotográfica da caixa da figura 6, ainda nao desmoldada
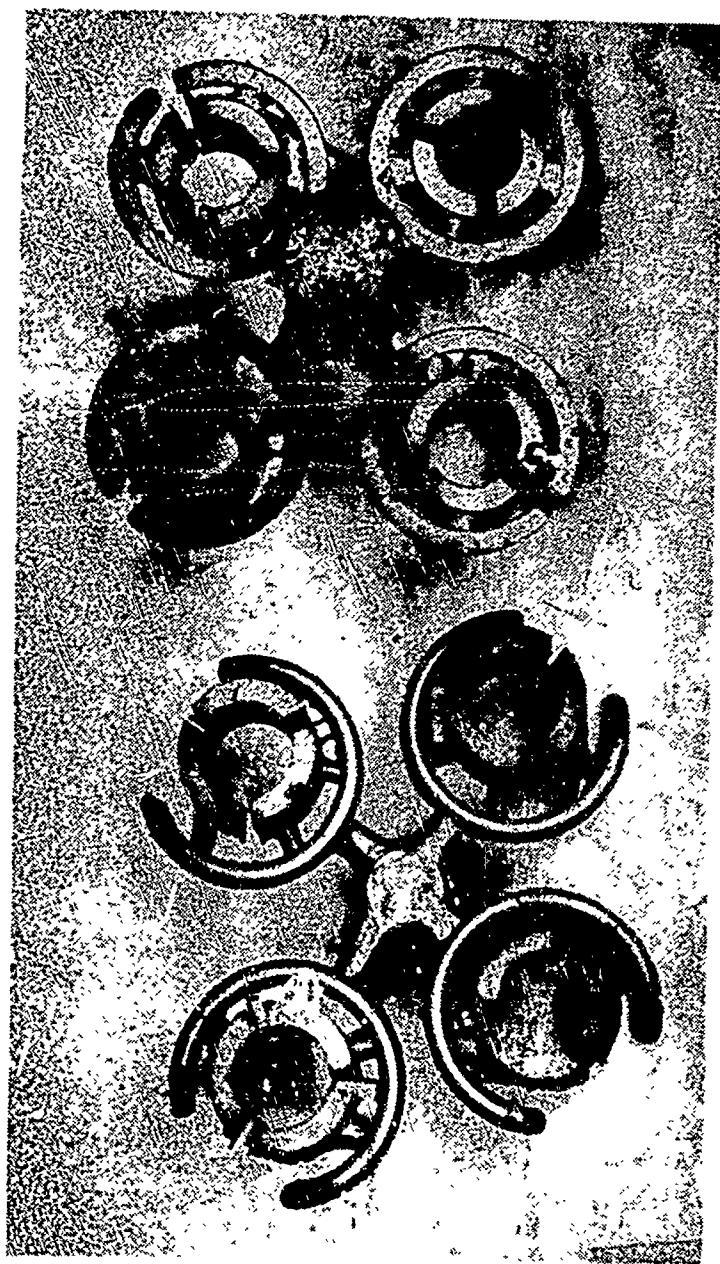
Fig. 8   Detalhes do ensaio com a caixa da figura 6

Fig. 9   Ultimo Tipo de Placa utilizada para o preparo de caixas

SOME ASPECTS OF METAL PROCESSING

by Erich G. Thomsen

Abstract

In a period of rapid advancement of science proficiency can no longer be achieved in any field of endeavor solely through practical experience. This is especially true in metal processing where it is necessary to apply advanced knowledge to the understanding of the behavior of metals in order to select the most suitable and the most economic process and material for a given industrial application.

A short review of the principles of plastic deformation is given and it is shown that forming characteristics and forming limits depend primarily on the state of stress. Accordingly, a classification of the major forming processes based on this concept is presented. In addition several methods of obtaining approximate solutions to forming pressures in forming problems are discussed and a comparison for an upsetting problem is given.

It is shown further that a treatment of forming problems is not complete unless a careful examination of the energy equation is made and every term of the equation properly accounted for. This ensures that no major errors are introduced when making energy balances.

Finally it is suggested that in practice the prediction of forces and energy alone is not sufficient and more thought must be given to the possibility of predicting among others, mechanical properties, surface finish, forming defects. It is

suggested therefore that more research be directed toward model studies in .hich all of the important parameters in forming and cutting processes can be evaluated. Once such information is available, the possibility exists that a mathematical model can be found which accurately describes the metal-processing operations.

1. Introduction

Success in manufacturing under present day economic competition requires exploitation of the most recent advances in the technology of metal processing. The advances in this field are numerous and the application to practice will often result in the modification of an existing process, its reduction in demand, or even its complete elimination. A few of the newer processes which have been accepted in production or are under consideration for application in practice are: continuous casting of steel slabs immediately followed by rolling, laser and electron beam welding, magnetic and explosive forming, spin forging, hydrostatic extruding, piercing and blanking yielding smoothly sheared edges, electrolytic and spark erosion machining, chemical milling, ultrasonic vibration-assisted cutting and forming.

During the time when innovations in manufacturing were few and when processes remained the same for long periods of time, it was possible to obtain the necessary "know how" for production through long years of experience. For example, the open-hearth process in steel-making remained essentially the same for nearly a century lasting until just a few years ago when liquid oxygen was introduced to speed up the refining process. Similarly the conventional metal-cutting process, except for increases in cutting speeds as better tool materials became available and better machine tools were built, remained essentially the same for almost as many years. Our rapidly advancing knowledge in science and technology, however, has changed all this and new ideas and new processes are constantly going into production over much shorter periods of time. Consequently, there is no longer the possibility to gain the necessary "know how" through long experience or by an uneconomical trial and error method. On the contrary, we must try to understand the underlying principles of a new idea or of a new process in order to predict performance with the aid of perhaps only a few critical experiments.

We will give a short account in this paper of the mechanism of plastic deformation and the important role that stresses play in forming operations. We will classify forming operations logically on the basis of stresses and will ilustrate the type of solutions available. We will point out further a certain danger that looms ahead unless we treat forming operations as systems and attempt to account

for the expenditure of all energies.

2. Rules for Plastic Deformation

It is a well-known fact that metals at low deformation rates (or strain rates) will deform at first elastically following Hooke's law. As deformation continues a critical stress will be reached where plastic deformation is initiated. This stress is called the yield point or yield strength depending on whether the point is well defined or occurs over a small region of straining. This critical stress is also often simply referred to as the yield stress. The yield stress is readily obtainable from a compression or a tensile test for the condition of uniaxial loading when the material remains reasonably isotropic. In the event the forming load occurs in the presence of multiaxial stresses then the yield stress or yield condition is generally accepted to be the effective stress $\bar{\sigma}$. This stress is also called the "von Mises yield condition" named for the mathematician von Mises who demonstrated its existence. It applies well to isotropic ductile metals encountered in forming problems, but no to brittle materials. For brittle materials the "Tresca maximum shear stress criterion" generally gives slightly better results.

The effective stress for a general combined state of stress is given by the square root of the sum of the squares of the three shear stresses, which act on the faces of an elemental cube, and the sum of the squares of the resultant shear stresses on the diagonal surfaces of the cube, which are due to the normal stresses acting on the faces of the cube. A general state of stress is shown in Figure 1. Thus, the effective stress (also known as a stress invariant) is essentially the root mean square shearing stress which takes on a critical value when plastic deformation is initiated. Thus the importance of the state of stress in yielding becomes at once evident. It reduces to the yield stress in tension or compression and can be evaluated readily from these tests under static conditions. Under dynamic conditions, or at temperatures other than atmospheric, its magnitude will not be constant and it will depend on the strain rate, metallurgical structure, and temperature. The behavior of the yield stress has been studied from a solid-state physics point of view, where the model is the imperfect crystal, characterized by dislocations. There are also some experimental data for some regions of stressing mainly during high temperature creep and in some scattered tests on impact loading. The available data, however, are incomplete and much more experimental work is required to give the forming engineer the necessary tools for analysis and for prediction of forming results.

After the yield condition has been exceeded the metal will deform plastic-ally in accordance with the rules of plastic deformation. If the metal is cold worked, it will become stronger because of the effects known as work-hardening. The equations relating the stresses to the plastic strains under these conditions are known as the plasticity equations. These equations are useful in calculating strains from the stresses, or vice versa provided the stress or strain path is known. During plastic deformation, the density of the material remains essentially constant, from which it follows that the sum of the finite normal strains is zero.

The resulting plastic deformation is irreversible and appears as heat en-ergy. In the event the deformation is discontinued or it is completed, only the elastic energy is recovered. This is due to the fact that the plastic energy is irreversible and essentially, all will have been converted into heat. The elastic strains associated with the accompanying plastic strains are small and usually can be ignored when compared with the much larger plastic strains. They cannot be neglected, however, when both strains are of the same order of magnitude. Also, the elastic strains can not be ignored when the straining during the deform-ation process was heterogeneous, because residual stresses will remain in the formed part. These residual stresses may be undesirable as illustrated by the springback of formed flanges during unloading.

3.   Classification of Forming Processes

From what has been said, it is clear that the forming stresses play an important part in forming problems. It would seem logical, therefore, to use the average state of stress as a criterion for classifying forming operations. Such a classification is given in Figure 2.

An inspection of Figure 2 reveals that the state of stress for large deform-ations is generally of a compressive nature. The processes carried out under these stresses are classified as squeezing operations and normally are used when a heavy reduction or change in shape is required as in rolling. The extent of deformation under these conditions can be very large because internal cracks, gas cavities, and pin hole porosity are repaired under the influence of compressive loading. One defect which limits the squeezing type of deformation is that of buckling, which occurs in upsetting operations when the workpiece is inadequately supported.

In the drawing group one or more of the forming stresses may have changed to tensile stresses. These forming operations are generally limited in the extent of deformation which may be achieved, because cracks and other defects may open

up rather than be healed and the process may be limited by fracture. In addition, in simple or combined tensile type of loading, the load condition may lead to a type of failure called necking. This failure is typical in a tension test of a ductile material and occurs at the maximum load. It is because the rate of reduction in area exceeds the rate of increase in strength due to work-hardening. Thus the weakest section, which reaches the maximum load first will start necking and will decrease in cross section more rapidly than any other. This type of failure is found also in stretching operations, bulging, stretch flanging, tube expanding, and others. It severely limits the extent of deformation possible.

The bending group of forming operations is principally concerned with the change in shape rather than reduction in cross section. The extent of deformation is much less than that in the squeezing group. The applied load is a moment and the stresses across the section of the workpiece vary from compression on the inner side of the bend radius to tension on the outer side. Thus, bending occurs, in the presence of stress gradients, which lead to residual stresses and to spring-back upon unloading.

The cutting group of metal-working processes can be divided into (a) processes where separation by shearing in a single cut take place as on a press brake and (b) where excess metal is removed by peeling a chip from the workpiece as in metal cutting. Both processes require plastic deformation in the cutting zone. It is important to note that in most forming processes the metallurgical structure of the workpiece is refined due to the plastic deformation process. This is not the case in machining where only the waste material is severely deformed, while the part being machined remains essentially unaffected.

4.   Some Methods of Solution to Forming Problems

The subject of determining forming loads and average forming pressures has been a favorite with investigators working in the fields of applied mathematics and engineering mechanics. Due to this effort, much is now known about solutions to forming problems and it is possible to obtain approximate forming pressures. Except for simple problems, however, general methods of obtaining exact solutions are not available. Consequently, an approximate theoretical solution still must be checked with experimental data to assure complete confidence. The reason rests with the assumptions required in the analysis, the effects of which cannot always be predicted. It is seen from Figure 2 that the state of stress in the metal under deformation is an important factor for classification. The state of stress is also important in the evaluation of the forming energy as will be shown subsequently.

The important methods of solution are (a) the Siebel uniform-energy method, (b) the Sachs slab method, (c) the Hencky slip-line method, (d) the Johnson-Kudo-Kobayashi upper-bound method, and (e) the Thomsen visioplasticity method. The solutions obtained with the methods a-d are compared in Figure 3 for a slab under compression in which the width remains constant (plane strain). Of the solutions the uniform energy method is the simplest and usually gives a value of forming load which is low because of neglect of shear deformation.

The average pressure is given by $p_{ave} = \int_0^{\bar{\epsilon}} \bar{\sigma}\, d\bar{\epsilon}$, where the definite integral is the energy per unit volume of the material deformed and is simply the area under the tensile or compressive stress-strain curve at an identical effective strain $\bar{\epsilon}$. The magnitude of p_{ave} is usually low since $\bar{\epsilon}$ cannot be determined exactly in an arbitrary forming problem since shearing strains are not known. A better value of p_{ave} is obtained if friction is also taken into account and if a shear coefficient is used to compensate for the neglect of shear deformation. For the upsetting problem shown in row (a) of Figure 3, experiments have shown that neglect of shear deformation is not serious for this problem and the value of $p_{ave}/\bar{\sigma}$ = 3.1 is a realistic value for maximum friction and for a condition when $l_f/h = 6.72$. Thus, $p_{ave}/$ = 3.1 where $\bar{\sigma}$ is the effective yield stress which must be taken as an average value.

The slab method is shown in (b) of Figure 3, which involves the integration of a linear differential equation and relates the stress gradient in the width direction x to the variable height h for the maximum condition of friction. The plasticity and yield conditions furnish the required interrelation between these variables. The solution is seen to be identical to that obtained with the uniform-energy method.

The slip-line solution for the same problem is shown in (c) of Figure 3. The figure to the right shows lines which indicate the maximum shear directions. These lines are drawn to satisfy the static stress-equilibrium equations for the given boundary conditions as well as for the velocity distribution of the metal. The equations shown on the left of the sketch permit the determination of the pressure distribution from which p_{ave} can be calculated. It is seen that the magnitude of $p_{ave}/\bar{\sigma} = 2.83$, is somewhat below the other two solutions.

The upper-bound solution is shown in (d) of Figure 3. This method consists of dividing the plastic region into small triangles as shown in the figure. In each of these triangles, the metal is assumed to flow as a rigid body and all plastic deformation occurs along the diagonals and along the die surfaces. The problem consists of determining the shear-strain rates along these lines and summing up all energies to obtain the total minimum energy required for deformation. It is seen that the value of $p_{ave}/$ = 2.9 lies between those of (a) or (b) and (d) of Fig. 3. It should be remarked that the agreement among these solutions is not always as close as in the foregoing example and only a comparison with results from an ex-

periment can furnish the basis for making the selection of the best solution.

Finally, visioplasticity is a method in which the metal flow field is determined from an experiment. This flow field is then used to calculate strain rates and the internal stresses. It utilizes the plasticity equations, the equilibrium equations and the stress-strain or strain-rate equations in analytical or graphical form. Figure 4 shows deformed grid lines of an aluminum extrusion. The particle velocities can be obtained by deforming the metal in small steps and noting the displacements of the grid-line intersections. The resulting axial-stress distribution is shown in Figure 5 obtained under the assumption that the flow was in steady-state.

The selection of the "best solution" for any given problem will depend on the resourcefulness of the engineer and his prime task is the choice of that method which appears to be most likely to give a useful answer. The engineer must be ingenious and the choice of the method and interpretation of the results must be made shrewdly.

5.   The Energy Equation

In the foregoing metal-working operations have been considered as isolated processes, much as one would consider a compression or expansion process of a gas in heat engines. Actually, however, metal-working operations are not isolated from their surroundings and one ought to consider systems in their entirety with all materials and energies entering and leaving accounted for. Such a consideration leads to the energy equation, which is in fact an energy-accounting equation and assures that no important quantities have been neglected.

While it is common practice to use the energy equation for a flow system in problems of thermodynamics, fluid flow, and heat transfer as the starting equation, metal-processing and production engineers often overlook its importance. However, its significance is at once apparent when the relative importance of each term in the equation is considered.

Let Figure 6 represent a metal-shaping device in which metal is flowing in at the bottom and leaves in a transformed state at the top. The shaping device, for example, may be a drawing die where the metal is continuously pulled through as in wire or bar drawing, it may be an extrusion apparatus where the metal is pushed through a die or it may be a metal-cutting zone in machining. The exact process for the present argument is unimportant, but let the dotted lines 1 and 2 represent

the boundaries between which the shaping process takes place. It is assumed that metal can enter and leave via sections 1 and 2 only, but the energy may flow across the boundar.es of the device. Then an energy balance may be written for the condition of steady state flow,

$$J (h_2 - h_1) + (v_2^2 - v_1^2)/2g + (z_2 - z_1) - JQ - E = 0, \qquad (1)$$

where in the foot-lb. system for each pound of material flowing,

h = enthalpy or heat content, Btu per pound of material
v = velocity, ft/sec
z = position of section, ft
Q = heat flow into system Btu/lb
E = mechanical, chemical, or electrical work done on system ft. lbs./lb
J = mechanical equivalent of heat (1 Btu = 778.28 ft. lbs.)

The several terms in the energy equation do not necessarily have the same significance in all metal-shaping processes of industrial importance.

The potential energy by virtue of position $(z_2 - z_1)$ can usually be neglected. Also, the kinetic energy term $(v_2^2 - v_1^2)/2g$ can often be ignored, since this energy is usually small when compared with the electrical or mechanical energy required to carry out a forming process. In an electrolytic machining process shown schematically in Figure 7, the work material is shaped by removing the excess material by electrolysis. This requires normally the discharge of a substantial dc current through a narrow gap between the negative tool (cathode) and the positive workpiece (anode). The electrolyte is alkaline and may be a dilute solution of common table salt ($NaCl$ in H_2O), modified with an inhibitor to prevent corrosion. It is pumped continuously through the gap to carry off the heat and the reaction products. Thus for the electrolysis, Equation 1 reduces to

$$J (h_2 - h_1) - JQ = E$$

or $$J (h) - JQ = E , \qquad (2)$$

where the energy E must be sufficient to account for the heat flow $-Q$ out of the system and the formation energy of the reaction products Δh required for the electrolysis. The current flow can be computed by making use of Faraday's law which states that one gram equivalent weight of metal is altered at each electrode for each 96500 coulombs (1 coulomb = 1 ampere per second). In the electrolysis hydrogen is liberated at the tool surface while excess metal is removed from the work surface. Thus, the process in essence is a deplating process, and the reactions in the narrow gap between the tool and workpiece due to the presence of ions in the solution and the passage of a strong current are as follows:

$$Fe + 2(OH)^- = Fe\ (OH)_2 + 2e^-, \tag{3}$$

and
$$H_2O + 2e^- = H_2 + (OH)^- \tag{4}$$
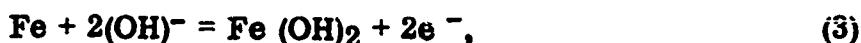
The reaction (3) occurs at the anode and liberates iron which first forms the insoluble compound $Fe(OH)_2$, but later in contact with air is oxidized to $Fe(OH)_3$ and can be filtered out, while reaction (4) liberates H_2 at the cathode. The tool is not affected by the reaction and for each atom of iron removed two electrons $(2e^-)$ must be supplied from an outside agency.

In order to calculate the enthalpy change in the system it is necessary to consider the heat of formation of the products in the reaction. Writing the complete reaction of Equations (3) and (4) results in

$$2H_2O + Fe = H_2 + Fe(OH)_2 + \Delta H \tag{5}$$

for which by substitution of the heats of formation at the standard temperature of 18° C and 1 atm. pressure results in the equation

$$2 \times 68 + O = 2(-50) + 136 + \Delta H. \tag{6}$$

Thus the formation of the reaction products results in the net energy absorption of

$$\Delta H = 100\ \text{kilocalories},$$

or
$$\Delta H = 100 \times 3.97 = 397\ \text{Btu/gram mol of iron} \tag{7}$$

This heat is absorbed in the formation of hydrogen gas and ΔH can be used to calculate Δh per lb. of iron removed from the workpiece, namely

$$\Delta h = \frac{w}{\text{mol (Fe)}}\ \Delta H = \frac{454}{55.84} \times 397 = 3130\ \text{Btu/lb.} \tag{8}$$

where $w = 454$ grams per pound of iron and one $\text{mol(Fe)} = 55.84$ grams is the molecular weight of iron.

The electrical energy E can be calculated from the required current for the electrolytic reaction and the voltage drop across the gap between the electrodes. The number of coulombs of electricity is obtained from Faraday's law, where the gram equivalent weight of iron is given by $\text{mol(Fe)}/2e^- = 55.84/2 = 27.42$ grams. Hence the electricity requirement in coulombs for each gram of Fe liberated is given by
$$\frac{96,500}{27.42} = 3510\ \text{coulombs/gram Fe} \tag{9}$$

Assuming that the removal rate is one pound of iron per minute, then the current requirement from Equation (9) is given by

$$i = 3510 \times \frac{454}{60} = 26,800 \text{ amperes} \tag{10}$$

Assuming further that the voltage drop between the electrodes is 10 volts according to observations in practice, then the power requirement would be

$$E = iV = \frac{26,800 \times 10}{100} = 268 \text{ kilowatts} \tag{11}$$

The heat removal rate (-Q) in Btu per minute from the electrolyte by refrigeration can now be calculated from Equation (2)

$$- JQ = E - J (\Delta H)$$

or

$$- Q = 268 \times 56.9 - 3130 = 12100 \text{ Btu/min,} \tag{12}$$

where 56.9 is the conversion factor from kilowatts to Btu per min. of heat flow. It is seen that in this process the energies are enormous and the current flow and the refrigeration rates (approximately 60 tons of refrigeration) are large. Commercial electrolytic machining units of about o..e third of the capacity of electrical energy are in practical use, but there is reason to believe that units as large or larger than the one discussed are feasible.

Consider next the application of the energy equation to a metalcutting problem. For simplicity a two-dimensional cutting process (orthogonal cutting) is considered as shown in Figure 8. The main energy for cutting is consumed in the region (a), where plastic deformation by shear takes place in a narrow zone. Additional energy consumption occurs at (b) through friction between the chip and tool face and to a smaller extent at (c) by friction between the flank of the tool and the machined surface. If one assumes that the cutting velocities are in the practical range, then the potential and kinetic energy terms of Equation (1) may again be neglected when compared with the plastic flow and friction energy terms, and the mechanical energy rate E' is given by

$$E' = F_c V \tag{13}$$

Thus the energy balance gives the equation

$$w'J \left[-Q + wc_p(T_2 - T_0) \right] = F_c V, \tag{14}$$

where:

w' =   lbs. of metal removed in the form of the chip, lbs/sec.

c_p =   specific heat at constant pressure, Btu/lb. deg. F

T_2 =   final average chip temperature, deg. F

T_O =   initial workpiece temperature, deg. F

F_c =   cutting force in the direction of motion, lbs

V =   cutting velocity, ft/sec

$-Q$ =   rate of heat flow out of the cutting region into the tool, the work-piece, and the surroundings, Btu for w' lbs

If the cutting process is carried out at higher speeds, say 300 ft/min or more, then the process approaches adiabatic conditions and the heat flow $-Q$ to the surroundings is nearly zero. Thus, we may write

$$Jw'c_p(T_2 - T_0) = F_c V \qquad (15)$$

and all energy will leave with the chip as internal energy. Thus, equation (15) permits the determination of F_c, when T_0, c_p and the rate of metal removal w' are known. Also the forces in forming as well as in cutting may then be calculated from the energy required for plastic deformation and friction.

While it was possible to neglect the kinetic energy term in the fore ing examples, this is not always justified. A case in point would be ultra-hig peed cutting at, say, 100,000 ft./min. This velocity was achieved on an exper nental basis by letting a projectile graze a stationary cutting tool, where the projectile was the moving workpiece. It was found in these experimental cutting tests that the chips were formed in continuous ribbons in a manner similar to conventional cutting. However, while chip formation may be similar, energies are not, and the kinetic energy term of Equation (1) can no longer be ignored, since the chip must be deflected at high speed by the tool in a direction parallel with the tool face. Table I shows calculated force and energy values for several cutting speeds and it is evident that the dynamic character of the process takes on major significance.

Table I

Effect of Cutting Speed on Energy Absorption
of SAE 1112 Steel Orthogonal cut

rake angle, $\nu = 0°$
undeformed chip thickness, $t_o = 0.008$ ips
depth of cut, $w_o = 0.20$ in
cutting ratio, $r_c = 0.47$

cutting speed ft/min.	Mechanical Energy ft. lb./lb	Kinetic Energy ft. lb./lb	Total Energy ft. lb./lb
10^2	-56,300	-0.03	-56,300
10^3	-56,300	-3.3	-56,303
10^4	-57,300	-336	-57,636
10^5	-142,500	-33600	-176,100

Conclusions

From the foregoing discussion it is evident that substantial progress has been made in understanding the mechanics of plastic deformation in forming processes and in utilizing this knowledge for the purpose of determining energies and forming loads. However, while the knowledge of forming loads and energies has theoretical importance, it may not have the same importance in practice. Among the problems that remain are: the determination of (a) structural change in the metal during deformation, state of work-hardening and strain, (b) damage imposed by forming through the formation of microcracks, (c) limits of forming imposed by necking, buckling, and fracturing, (d) effect of hydrostatic pressure and high strain rate on flow and forming limits, (e) mechanism of friction under conditions found in metal forming, (f) stress-strain rate-temperature relationships for common metals and range of conditions used in practice, (g) surface quality and surface finish.

Some information is available but it is spotty and it is incomplete. Necking for example, has been studied and predictions have been proposed for which experimental evidence is lacking, especially for combined stresses and high-rate

forming. Buckling has been investigated and equations are available for prediction but little or no experimental evidence is available. Fracturing, also, has been under study for many years, but only brittle fracture is reasonably well understood, whereas our knowledge of ductile fracture of metals is incomplete. In addition it has been shown that yielding and flow do not seem to be influenced by hydrostatic pressure, but it is not known what effect this pressure has on fracture and on other forming limits.

It appears that many of these unsolved forming problems are not amenable to analysis alone and that more experimental data are needed. However, unless the experiments are chosen in such a way that generalization is possible, the results will have only limited application. Careful planning of experiments will be an essential ingredient to success. The author believes that wider use should be made of model studies in order to gain a better insight into actual deformation processes in aiding in the determination of texture, strain, residual stresses, surface finish and other important properties of the finished workpiece.

In conclusion it should be said that an important consideration in metal-working problems in the future would be to take into account not only forces and energies required in forming operations but to explore the interaction between the final shape and properties of the formed part, and the material and its structure, its initial shape, the tools, the forming machines and the deformation processes. Hence, the model for a forming process besides energies should include such items as are shown in Figure 9, which should let us better describe all important properties of the material before and after forming.
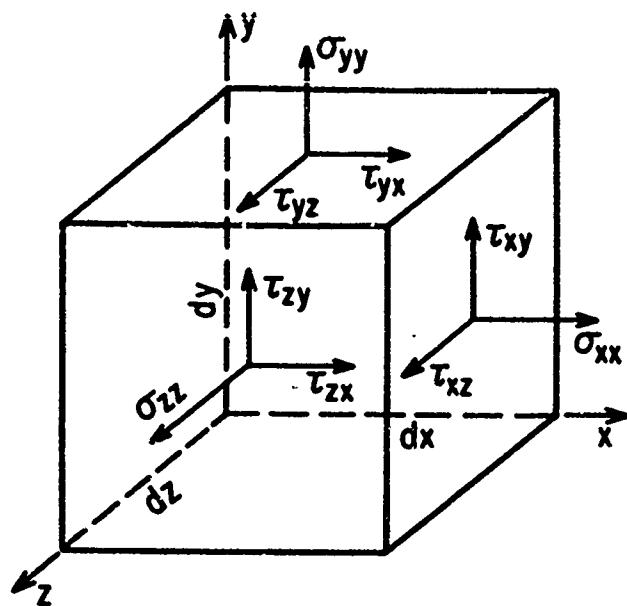
Fig. 1   State of Stress at a Point
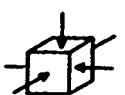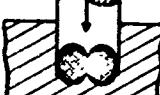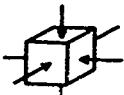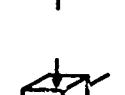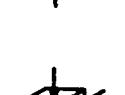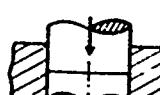
Fig. 2   Some Metal-Forming Operations

BASIC DEFORMATION MECHANISM	SKETCH OF OPERATION	STATE OF STRESS (AT SOLID SQUARE/IN SKETCH)	NAME	BASIC DEFORMATION MECHANISM	SKETCH OF OPERATION	STATE OF STRESS (AT SOLID SQUARE/IN SKETCH)	NAME
SQUEEZING			SPIN FORGING OF CONES	BENDING			STRETCH FLANGING
SQUEEZING			SWAGING	BENDING			SHRINK FLANGING
DRAWING			BAR AND WIRE DRAWING	BENDING			SEAMING
DRAWING			TUBE DRAWING	CUTTING (CHIPLESS)			PRESS SHEARING AND CUTTING OFF
DRAWING			DEEP DRAWING	CUTTING (CHIPLESS)			NOTCHING AND NIBBLING
DRAWING			EMBOSSING	CUTTING (CHIPLESS)			PIERCING AND BLANKING
DRAWING			STRETCH FORMING	CUTTING (CHIP FORMING)			SHAVING
DRAWING			BULGING	CUTTING (CHIP FORMING)			MACHINING (SINGLE AND MULTI POINT TOOLS)
DRAWING			ROLL FORMING	CUTTING (CHIP FORMING)			GRINDING
BENDING			STRAIGHT FLANGING				

Fig. 2   (Cont.)
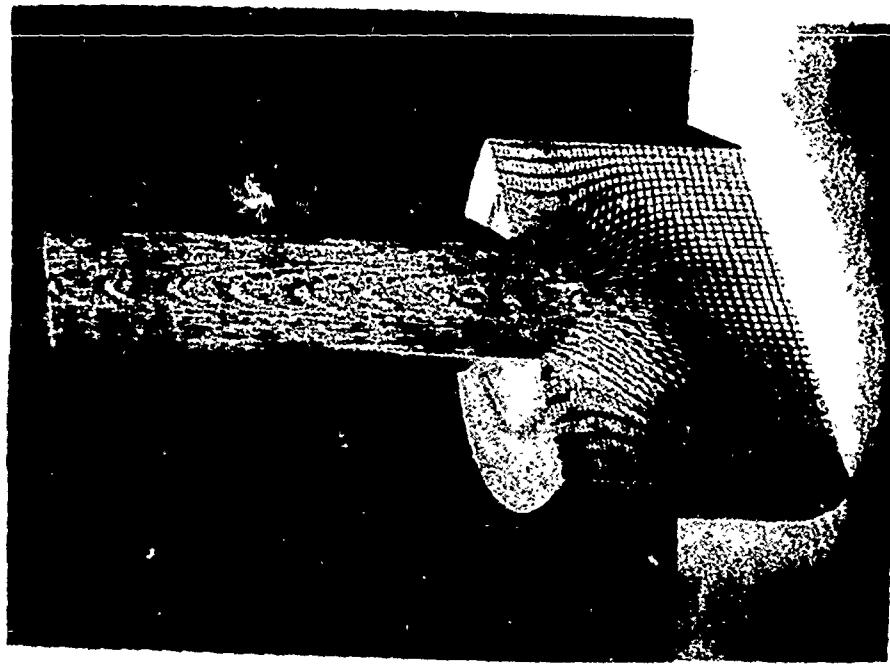
Deformed Grid Lines in an Extrusion

Fig. 4

PLANE STRAIN

$\ell_f / h = 0.72$; PERFECTLY ROUGH DIES

a. UNIFORM-ENERGY METHOD

$$\frac{P_{ave}}{\bar{\sigma}} = \frac{2}{\sqrt{3}}\left(1 + \frac{1}{4}\frac{\ell_f}{h}\right) \approx 3.1$$

b. SLAB METHOD

$$\frac{P_{ave}}{\bar{\sigma}} = \frac{2}{\sqrt{3}}\left(1 + \frac{1}{4}\frac{\ell_f}{h}\right) \approx 3.1$$

c. SLIP-LINE METHOD

$\sigma_z = -p - k \sin 2\phi$

$\sigma_x = -p + k \sin 2\phi$

$\tau_{zy} = k \cos 2\phi$

$k = \bar{\sigma}/\sqrt{3}$

$$\left.\right\} \quad \frac{P_{ave}}{\bar{\sigma}} = 2.83$$

d. UPPER-BOUND METHOD

$$\frac{P_{ave}}{\bar{\sigma}} = \frac{2}{\sqrt{3}}\left[\left(m - \frac{1}{2}\right)\frac{h}{\ell_f} + \left(\frac{m - \frac{1}{2}}{4m - 1}\right)\frac{\ell_f}{h}\right]$$

$= 2.9 \qquad (m=3)$

Fig. 3 Some Methods of Solution Applied to an Upsetting Problem
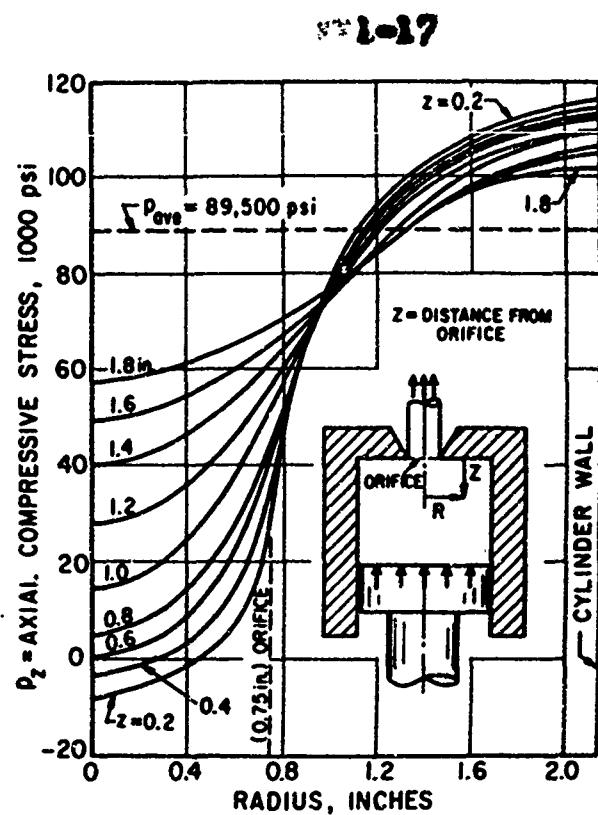
Fig. 5   Axial Stress Distribution in a 4.3 in. Diameter Aluminum Billet
Extruded into a 1.5 in. Dia. Rod.
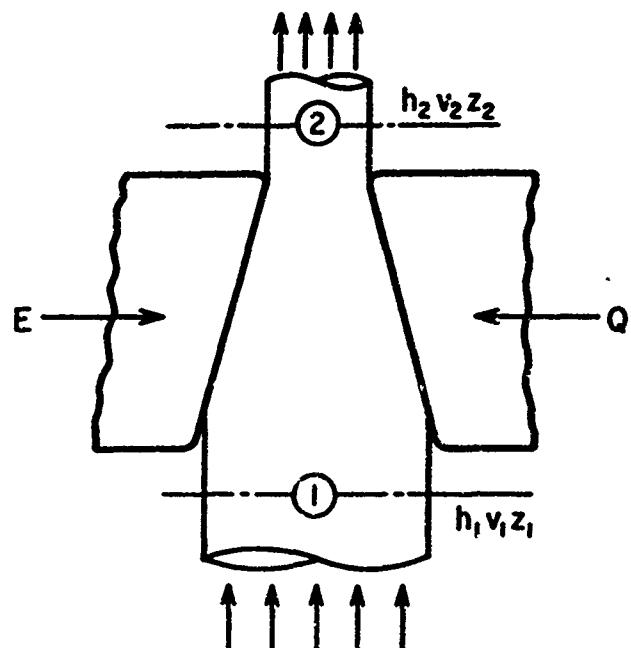
Fig. 6   Schematic Diagram of Metal Shaping Device

Fig. 7   Schematic Diagram of an Electrolytic Machining Process
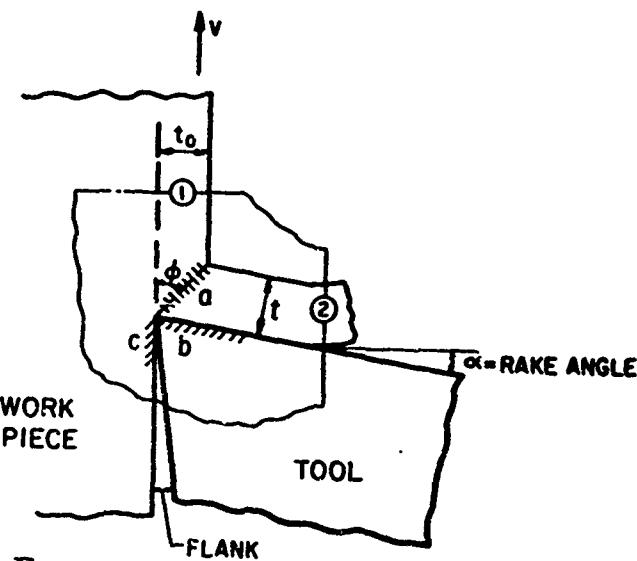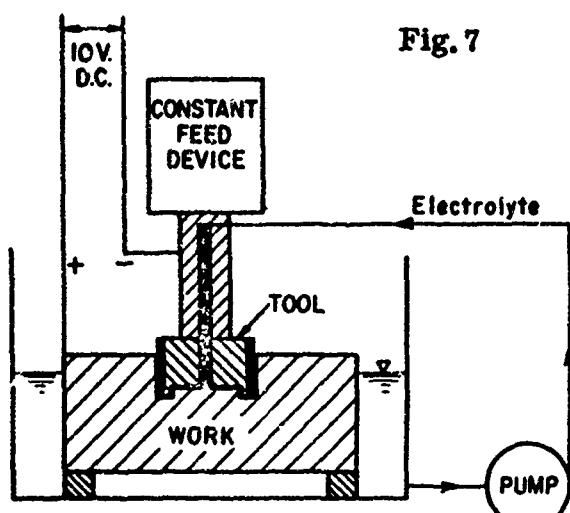
Fig. 8   Metal Cutting Zone as an Energy Transformation Device
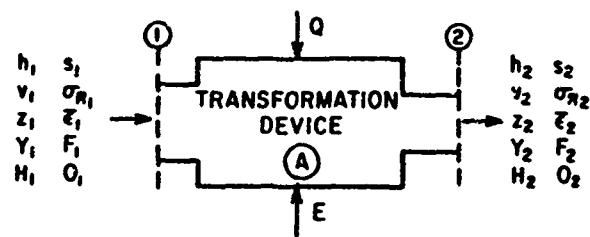
h = enthalpy
v = velocity
z = elevation
s = structure
σ_R = residual stress
$\bar{\epsilon}$ = finite strain
F = surface finish and lay
Y = yield strength
H = hardness
O = orientation of defects(Mech. fibering)
[at (A), complete information on process is required]

Fig. 9   Modified Sketch of Energy Transformation Device Showing Additional Information of Vital Interest in Forming Problems

TRI-SERVICE COORDINATED METAL WORKING AND PROCESSING PROGRAM

by Norman L. Reed

Introduction

Land, sea, and air are the natural divisions of the earth on which we live. The responsibilities of the United States Army, Navy, and Air Force are mainly parallel to these three natural states. The three services work together in an endeavor to maintain a national posture. In like manner, researchers, scientists, and engineers work together in the metals working and processing program to translate research knowledge into useful engineering and structural metals.

Having recognized the need to be ever moving forward to meet the requirements placed on our Army agencies and to minimize the time interval between research knowledge and the final production or manufacture of useful "hardware", it is evident that concerted effort is justified to improve old and invent new ways of handling and processing metals into usable shapes with optimum properties under quality-controlled conditions.

In general, industry currently produces heavy tonnages of the usual engineering metals to rather rigid requirements and these metals are, in turn, shaped, joined, and fabricated into the thousands of items used daily in our homes, factories, schools, automobiles, etc. The endeavor of the Army, working in close cooperation with the Navy and Air Force, is to develop methods of converting the unusual and costly metals into closely controlled shapes, sizes, and contours while avoiding excessive loss or waste of these metals as they become functional parts of a system.

Although quality control or process control is not a part of this program per se, it is expected that the working and fabrication of the unusual metals or unique shapes of the more standard metals will reveal that new quality control

techniques will be required. The research and development teams worl 1g on the program being reported here, having developed new processing techniques, will be of great assistance to those responsible for developing quality assurance techniques.

Additional background relative to the establishment of the coordinated metal working and processing program included an assignment by the Department of Defense to the Materials Advisory Board of the National Academy of Sciences to make an exploratory investigation on the topic of deformation of metals. An ad hoc committee was formed for this purpose. Although the committee has been dissolved, its deliberations interested many segments of the Department of Defense and in part instigated the holding of a research conference in August 1962*, on "Fundamentals of Deformation Processing", which was sponsored by the U.S. Army Materials Research Agency (AMRA) in conjunction with Syracuse University under the chairmanship of the author of this paper. This conference, attended by carefully selected talent, did much to solidify the known information of the universities, industry and Government on this subject.

Participating organizations

Under the authority of the Department of Defense, the Army, Navy, and Air force joined in the establishment of the current Metalworking Processes and Equipment Program (MPEP) in the latter part of 1962. The National Aeronautics and Space Administration was also interested and joined the endeavor. The Navy was assigned the responsibility of coordinating the program and Mr. Thomas F. Kearns was named Chairman of the Government Steering Group of the MPEP. The above three services and NASA have membership in this group, in addition to other representation from the Department of Defense and the Defense Metals Information Center. This group meets approximately three times a year and deliberately chooses to assemble at locations where considerable activity in metal working is taking place.

Following the frequent custom of the Department of Defense to assure as broad as possible advice on a particular subject, the Department requested the National Academy of Sciences to establish a Metalworking Processes and Equipment Committee under its Materials Advisory Board (not ad hoc committee, as

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*Under a contractual agreement, the proceedings of this conference have been published by Syracuse University Press in a book bearing the same title.

previously reported). Members of this committee are currently drawn from four universities, from four prominent companies in industry, and from two research institutes or laboratories. It convenes under the chairmanship of Dr. William Rostoker of the Research Institute of Illinois Institute of Technology.

Purpose of the program

The program is designed to fulfill a continuing need to assess research information on metal deformation, devise and promote improved metal processing equipment, and recommend processing conditions that will yield optimum characteristics in the variety of metals required by the Department of Defense, some of which are frequently difficult to process. Three phases of this effort have been recognized. They are:

a. compilation of existing knowledge of the deformation characteristics imposed by the various processes, *

b. recommendation of programs necessary to overcome gaps in the present knowledge, and

c. design, construction, and operation of new metalworking equipment.

Activities under the program

Attention has been focused to a considerable extent on the deformation characteristics of refractory metals, on beryllium, and on super alloys, with initial emphasis on the rolling process. Attention to extrusion, spinning, drawing and the like will be initiated at a later date. Consideration of strain rate, effect of temperature, anisotropy, crystallographic texture, and of ultrasonic energy and high pressure have been included in the program.

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*Processing of metals in the solid state includes cold drawing, cold extrusion, rolling, etc.

It has been obvious from the start that dissemination of the results of the program was essential: thus, preparation of reports that would acquaint processing equipment designers and manufacturers with the advances in deformation processing has been included.

A reasonably complete listing of programs in Government laboratories or conducted under contract, either planned, under way, or completed, has been compiled. As an aid in visualizing the program, a list of typical efforts is attached as Appendix A, which notes the sponsors as well as those conducting the research.

Meetings of the Government Steering Group of MPEP have been held at the Bureau of Naval Weapons, at Wright-Patterson Air Force Base, and at AMRA, with opportunity to observe some of the activities associated with the program. There were three presentations made to the Steering Group at the AMRA meeting. These were:

a.   Thermomechanical Treatment of Steel - Dr. E.B.Kula

b.   Metal Behavior in Rolling and Wire Drawing - Mr. E.DiCesare

c.   Development of Anisotropy in Titanium - Mr. F.R.Larson

The Steering Group sponsored a "Symposium on Ultrasonics in Metal Deformation" in June of 1963. The Defense Metals Information Center (DMIC) prepared a report of the symposium DMIC Report 187, dated 16 August 1963, entitled "The Application of Ultrasonic Energy in the Deformation of Metals". Some excerpts from this are given in Appendix B.

In addition, a second symposium on high pressure in metal-deformation processing was held in October 1963. The DMIC was likewise charged with the responsibility of reporting on this meeting and issued DMIC Report 199, dated 2 March 1964, entitled "The Application of High Pressure in Metal-Deformation Processing". Some excerpts from this report are given in Appendix C.

Materials advisory board program

As noted previously at the request of the Department of Defense, the

Materials Advisory Board had established a Metalworking Processes and Equipment Committee composed entirely of non-Government scientists and engineers. This committee, acting under the auspices of the National Academy of Sciences, has been asked to provide advice and assistance to the Department of Defense in the organization and conduct of an integrated program on the advancement of deformation theory and its application to the manufacturing process. The letter of assignment from DOD noted (a) that basic and applied research has resulted in an increase in knowledge of metals deformation phenomena; (b) an interservice program (MPEP) involving participation of a Government Steering Group has been initiated to reduce this knowledge to practice; (c) that the cooperation of the scientific community and the metal working equipment producers and users would be desirable in MPEP; and (d) that an MAB committee should be organized to promote this cooperation. The ground rules for the MAB committee are as follows: (a) to serve as a forum for discussion of deformation technology among well-informed individuals from industry, academic organizations, and Government; (b) to review and guide Army, Navy, and Air Force programs, both present and proposed; and (c) through the issuance of advisory reports, to make recommendations for initiation or the conduct of research and development in deformation processes.

The first meeting of the MAB committee was held in November of 1963 in Chicago, Illinois. The committee agreed to focus its attention upon the direction and balance of the research and development projects in the early stages of effort and on those projects now being planned. It is also possible that the MAB committee will be asked to review and comment on the specific proposals received by the Services.

For longer range activity the committee suggested that it could concern itself with (a) discussions involving exploration of unexploited areas which might lead to the development of new manufacturing techniques; (b) arranging for trade association and industrial representatives to discuss the obstacles and factors which limit design and operation of present equipment; and (c) investigating the fruitful avenues for displaying the findings of the Government program to a large segment of the engineering community.

This committee recognizes that the disciplines of primary importance to the current program are physical metallurgy, mechanical metallurgy, materials engineering, physics, applied mechanics, and mechanical engineering.

A second meeting of the MAB committee was held in April of 1964. The presentations covered capacities and limitations of present ultrasonic generators and of high-pressure hydrostatic systems as applied to metalworking, a review of some of the effort underway, a review of some proposals received, a discussion on continuum mechanics, a paper on the applicability of flow stress and strain measurement to the analysis of real deformation processes, and a paper on super-

plasticity.

Summary

The Department of Defense has embarked on a research and development program covering the facets of metalworking and processes that now limit our ability to produce, as economically as possible, structural metals (most frequently the highcost uncommon metals) with optimum properties and in optimum shapes. The approach reported is quite typical of those used by the three Services of the Department of Defense to thoroughly coordinate the many facets of a broad program. To date the program is "young". We confidently expect that it will have profound effects on the availability, in quantity, of a variety of metals with shapes and characteristics that are not now attainable. Results of the effort have been and will continue to be reported in the open literature.

APPENDIX A

LISTING OF TYPICAL EFFORTS RELATING TO
METALWORKING PROCESSES AND EQUIPMENT PROGRAM

Category I.   Modes of Deformation

Typical Programs

Flow and Fracture Characteristics of Titanium
Flow and Fracture Characteristics of Tungsten and Tungsten Alloys
Flow and Fracture Characteristics of Beryllium
Tungsten Single Crystals
Bauschinger Effects
Fracture in Polycrystalline Tungsten
Effect of Precipitates in Plastic Flow at Low Temperatures

Typical Sponsors

Army Materials Research Agency
Navy - Bureau of Weapons
Air Force - Materials Laboratory

Typical Research Groups

Franklin Institute
Linde Company
European Research Associates
Battelle Memorial Institute
Cornell Aeronautical Laboratory

Category II.   Strain Rate and Temperature Studies

Typical Programs

Effect of High Strain Rates on Mode of Deformation and Ductile
Brittle Fracture Transistion
Determination of Shear Forming Parameters for 18%Ni Alloys for
Gun Tube Production
Warm Working of Armor Steel for Increased Toughness and Strength
Polycrystalline Aggregates in Metal
Dynamic Plastic Deformation in Aluminum Single Crystals
Stress-Strain Characteristics of Materials at High Rates of Strain
Effect of Strain Rate and Temperature on Deformation Character-
istics of Beryllium, Tungsten, and Udimet 700
Development of Explosive Forming Techniques in Metal Forming
Extrusion, Rolling, Forging of Refractory Metals
Extrudability Parameters for Ingot Extrusion
Deformation and Fracture of Crystalline Solids Under Dynamic
Loading
Cyclic Strain Accumulation Under Complex Multiaxial Loading
Basic Parameters of Metal Behavior under High Energy Rate Forming
Metal Behavior in Rolling and Wire Drawing
Warm Swaging of Refractory Metals

Typical Sponsors

Army - Watervliet Arsenal
Army - Tank and Automotive Center
Army Research Office - Durham
Army Materials Research Agency
Navy - Bureau of Weapons
Air Force - Materials Central
Air Force - European Research Office
National Aeronautics and Space Administration

Typical Research Groups

Army - Watervliet Arsenal
University of California
Southwest Research Institute
University of Texas
Naval Ordnance Test Station

New England Materials Laboratory
Central Institute of Industrial Research - Norway
Westinghouse Electric Corporation
Wright-Patterson Air Force Base Metals Laboratory
Convair Division - General Dynamics
University of Liverpool - England
University of Illinois
Rutgers University
Aerojet General Corporation
Lewis Research Center - NASA
Army Materials Research Agency
Arthur D. Little Company
Frankford Arsenal

Category III. High Pressure Effects

Typical Programs

Structural Changes in Anisotropic Materials Under Hydraulic
    Pressure to 40,000 Atmospheres
Hydrostatic Extrusion of Tungsten and Beryllium Under High Pres-
    sures
Drawing Sheet Metals Under Hydrostatic Pressure
Hydrostatic Extrusion of Refractory Metals

Typical Sponsors

Army - Watervliet Arsenal
Navy - Bureau of Weapons
Air Force - Materials Central
National Aeronautics and Space Administration

Typical Research Groups

Army - Watervliet Arsenal
Pressure Technology Corporation of America
General Electric Corporation Research Laboratory
Battelle Memorial Institute

Category IV.   Ultrasonic Effects

Typical Programs

Effect of Ultrasonics, Temperature and Strain Rate on Deformation
Characteristics of Structural Metals
Effect of Ultrasonics on Deformation Characteristics of Metals
Effects of Ultrasonics on Wire Drawing
Application of Ultrasonics to the Rolling Process
Feasibility of Ultrasound for Determination of Structural Inhomo-
geneities and Residual Stress in Various Metal and Non-
Metal Structures

Typical Sponsors

Navy – Bureau of Weapons
Air Force – Materials Laboratory
Cincinnati Milling and Grinding Machines Inc.

Typical Research Groups

Cincinnati Milling and Grinding Machines Inc.
Naval Ordnance Test Station
University of Michigan
Westinghouse Electric Corporation
University of Vienna

Category V.   Orientation and Texture Studies

Typical Programs

Strength and Plasticity of Anisotropic Metals
Structural Changes in Anisotropic Materials by High Pressures
Orientation and Texture Studies During Rolling of Titanium Sheet
Materials .
Effect of Crystallographic Textures of Several Anisotropic Metals
on Deformation
Deformation and Texture Studies in Tantalum and Molybdenum
Thermo-Mechanical Studies on Beryllium Sheet

Typical Sponsors

>   Army Materials Research Agency
>   Navy - Bureau of Weapons
>   Air Force -- Materials Laboratory

Typical Research Groups

>   Army Materials Research Agency
>   Massachusetts Institute of Technology
>   Air Force - Materials Laboratory
>   Army - Watervliet Arsenal
>   Pechiney Company - France
>   Franklin Institute

Category VI.   Friction and Wear Studies

Typical Programs

>   Extrusion Lubricants
>   Effect of Surface Films on Mechanical Properties
>   Surface Effects of Solids
>   Effect of Surface on Mechanical Behavior of Metals

Typical Sponsors

>   Air Force - Materials Laboratory
>   Navy -- Bureau of Weapons

Typical Research Groups

>   Air Force - Materials Laboratory
>   Thompson Ramo Woolridge, Inc.
>   The Martin Company
>   General Mills, Inc.
>   Martin-Marietta Corporation

Category VII.   Mechanics of Processing

Typical Programs

Mechanichs of Deformation in the Rolling Process Using Visioplas-
ticity Methods of Analysis
Work-Hardening Phenomena
A Study of Forging Variables
Hot Working of Metal

Typical Sponsors

Army - Frankford Arsenal
Navy - Bureau of Weapons
Air Force - Materials Laboratory

Typical Research Groups

Army - Frankford Arsenal
University of California
United Aircraft Corporation
Battelle Memorial Institute
University of Birmingham, England

Category VIII.   Superplasticity

Typical Program

Evaluation of Superplasticity Phenomena Applied to Difficult-to-
Process Metals

Typical Sponsor

Army - Frankford Arsenal

Typical Research Group

Army - Frankford Arsenal

APPENDIX B

Excerpts from DMIC Report 187 :

THE APPLICATION OF ULTRASONIC ENERGY IN THE DEFORMATION OF METALS

Report on an Informal Symposium

Summary

"On June 21 a symposium was sponsored by the Bureau of Naval Weapons on the application of ultrasonic energy in the deformation of metals. At this session, a number of investigators actively working in the field reported informally on the results of their research. The reports revealed that the results achieved by incorporating ultrasonic transducers into conventional metal-forming and -cutting operations are sufficiently promising that the technique merits further attention. Data are available to indicate that application of ultrasonic vibrations during metalworking can increase speeds, lower forces, and improve surface finishes. All of these results have been obtained without any observed difference in properties between ultrasonically and conventionally fabricated parts.

"During the meeting the use of this technique was demonstrated in many common forming operations (drawing, grinding, tapping, extrusion, rolling), mainly on materials with low yield strength and low creep resistance (zinc, lead, aluminum, etc). There was no agreement as to the cause of the improved fabricability, both a lowering of the yield stress and a reduction of friction being suggested.

"Some details on design of experimental and pilot-plant equipment are given".

Presentations were made by:

Dr. B. Langenecker, Naval Ordnance Test Station, China Lake, California.

Professor L.V. Colwell, University of Michigan, Ann Arbor, Michigan.

Mr. A.T. Robinson, Naval Ordnance Test Station, China Lake, California.

Dr. C.A. Boyd and Mr. N. Maropis, Aeroprojects, Inc., West Chester, Pennsylvania.

Dr. C.A. Boyd and Mr. H. Kartluke, Aeroprojects, Inc., West Chester, Pennsylvania.

Mr. B. Mainwaring, Uniform Tubes, Inc., Collegeville, Pennsylvania.

Dr. W.B. Tarpley, Jr., Aeroprojects, Inc., West Chester, Pennsylvania.

Dr. R.R. Weber, Cincinnati Milling Machine Company, Cincinnati, Ohio.

Mr. H.L. McKaig, Jr., Aeroprojects, Inc., West Chester, Pennsylvania.

Suggestions For Future Work

"(1)   If the use of ultrasonics is to spread, one of two conditions must be met: its use must either make the production of materials and shapes now being fabricated more economical or it must permit the fabrication of materials which cannot now be handled by conventional processes. A good example of the former is the report of Uniform Tubes, Inc., that, by using ultrasonics, the number of drawing reductions can be reduced from three to two in producing thin-walled aluminum tubing. On the other hand, few data have appeared which would indicate that ultrasonics will be a help in fabricating refractory or brittle materials. The most sensational results have been obtained on materials such as zinc, lead, aluminum, and copper which are quite ductile and have little creep resistance. From the viewpoint of the MPEP program, interest in ultrasonic forming is contingent on its ability to fabricate materials possessing good creep resistance. Since it has not been shown that ultrasonic forming will provide a solution to this problem, a demostration of improved fabricability in any one of a number of refractory alloys should have top priority. For example, F48 is a columbium-base alloy which showed good promise as a high-temperature material but which has been largely written off, mainly due to its lack of fabricability. Another case is the alloy composition Nb_3Zr which could be the basis for large-scale introduction

of superconductivity in the electrical industry.

"(2)   In using ultrasonic energy in metal deformation, design of equipment and monitoring of experiments appear to be difficult. The installation of ultrasonics requires experience in use of transducers and in the design of resonating systems. Furthermore, questions such as where to apply the vibrations, should vibration be axial, radial, or flexural; and what frequencies and amplitudes are optimum must be answered separately for each operation and each piece of equipment. Equipment must be designed which will optimize the delivery of ultrasonic energy to the workpiece and guidelines for answering the above questions should be developed. The monitoring problem must also be considered. It is easy to measure the power input to the transducer, but very little has been done to measure the power delivered to the workpiece. Measurements of temperature rise of the workpiece have not been reported, although this may be an important effect as suggested by the buildup of metal on wire-drawing dies in experiments at the U.S. Naval Ordnance Test Station. Finally, although speeds are relatively easy to measure, caution should be used in analyzing reported drawing tensions since sophisticated rapid-response electronic gear must be used to make such measurements accurately. More data on speeds, efficiencies, and tensions are certainly needed. Programs such as that initiated at Cincinnati Milling Machine should provide the answer to the question of whether friction or yield-point effects (or both) are causing the reported improvements in fabricability.

"(3)   Even if the yield-point effect proves to be of minor practical importance in forming operations, its undoubted existence presents a challenge to the theoretician. It is strange that the large amount of prior effort in the field of internal friction did not predict this effect. Its cause is also unknown, and a valid mechanism for absorption of ultrasonic energy is needed. Transmission electron microscopy of conventionally and ultrasonically formed materials would be helpful. Perhaps fatigue data will give information on what effects are to be expected at low frequencies and will be useful in determining optimum frequencies".

APPENDIX C

Excerpts from DMIC Report 199

THE APPLICATION OF HIGH PRESSURE IN
METAL-DEFORMATION PROCESSING

Report on an Informal Symposium of the
Metalworking Processes and Equipment Program

Summary

"On October 3, 1963, a symposium was sponsored by the Bureau of Naval
Weapons, Metalworking Processes and Equipment Program, on the application of
high pressure in metal-deformation processing. Informal talks were given by
eight investigators actively working in the field, covering both fundamental and
applied aspects of high pressure effects.

"Past research, largely by Bridgman, has shown that superimposed hydro-
static pressure can significantly increase the ductility at fracture of various mater-
ials. These observations have stimulated considerable interest in applying this
hydrostatic-pressure effect to metal deformation processing, where it was anti-
cipated that improved ductility and fabricability of brittle materials could be re-
alized. Hydrostatic extrusion and hydrodynamic compressive forging were two
such fabrication techniques discussed at the symposium, and preliminary results
were found to be encouraging. Another fabrication process that will be investigated
in the near future is sheet drawing, where the effect of superimposed pressure on
drawability will be evaluated.

"Although it is generally observed that testing under high pressure im-
proves the ductility to fracture, it was noted that pressure cycling did not improve
either the strength or ductility of steels containing various amounts of carbon. In
addition to the mechanical-property effects, hydrostatic pressure has been found

to affect measurably, numerous metallurgical properties of metals and alloys.
These include modes of deformation: kinetics of recovery, recrystallization, and
grain growth; and phase stability".

Presentations were made by:

Mr. T.F. Kearns, Head, Metals Branch Bureau of Naval Weapons, "High
Pressure Studies in Relation to MPEP".

Dr. A.Bobrowsky, Pressure Technology Corporation, "Background on
Deformation of Metals Under High Pressure".

Mr. H.L.D. Pugh, National Engineering Laboratory, East Kilbride,
Scotland, "Effect of High Pressures on Metal Deformation".

Dr. A.Kulin, ManLabs, Inc., "Effect of High Pressure on Metals".

Mr. T.E. Davidson, Benet Research and Engineering Laboratories,
Watervliet Arsenal, "Effects of Pressure on Structure and De-
formation of Metals".

Mr. Robert Fiorentino, Battelle Memorial Institute, "Hydrostatic Ex-
trusion".

Dr. H.C. Rogers, General Electric Company, Research Laboratory,
"Drawing of Sheet Metal".

Mr. Richard M. Cogan, Thomson Engineering Laboratories, General
Electric Company, "Hydrodynamic Compressive Forging".

Suggestions for Future Work

"Process Development

"Although the hydrostatic-pressure effect has been applied with encouraging
results (at room temperature) to hydrodynamic compressive forging and hydrostatic
extrusion, more research and development is required to fully evaluate these fab-
rication techniques. In particular, it is important to determine the subsequent.
mechanical properties of materials fabricated by these means to check for uniform-

ity and to compare with the properties of materials fabricated by more convention-
al techniques. Future work should also include efforts to apply these fabrication
methods at elevated temperatures. Development of equipment with high-temper-
ature capabilities will probably be necessary before these techniques can be suc-
cessfully applied to fabrication of high-strength, high-melting-point materials.
Additional research appears to be warranted to determine the mechanisms of
lubrication during hydrostatic extrusion.

"Modes of Plastic Deformation

"(1)   Considerable work is required to evaluate the modes of plastic de-
formation of materials tested with a superimposed hydrostatic pressure (e.g.,
slip, twinning, stacking faults, deformation bands, and kink bands). The utilization
of special techniques, such as transmission electron microscopy, has provided
substantial information regarding deformation mechanisms, but this type of work
has not, as yet, been applied extensively to materials deformed under high hydro-
static pressures.

"(2)   Recent (unpublished) experiments by E. P. Bullen and H. L. Wain in
Australia have shown that brittle, recrystallized chromium becomes ductile at
ambient temperature and pressure after being subjected to large hydrostatic pres-
sures. For example, the room-temperature (1 atmosphere) ductilities were found
to be as follows:

"(a)   Unpressurized - 0 per cent elongation, 0 per cent reduction
in area

"(b)   Pressurized at 10^4 atmospheres - 65.4 per cent elongation
47.3 per cent reduction in area

The ductilizing effect is probably the same as that due to prestrain-
ing above the ductile-to-brittle transition temperature. Prestraining removes the
yield point by the introduction of fresh dislocations, and it is probable that the ab-
sence of a yield drop after pressurization is also caused by generation of mobile
dislocations. This in turn could lower the propensity for twinning, which is one
potent mechanism of crack initiation in chromium (e.g. at twin/twin and twin/
grain boundary intersections). The mechanism of dislocation generation under
pressure is still now known however, and it appears that some further research
is warranted. In addition to such investigations, it might be of practical import-
ance to determine whether complex shaped parts of brittle materials (which can-
not be conveniently prestrained by normal methods) could be ductilized by hydro-
static pressurization".

SOME TECHNICAL ASPECTS OF THE
U.S. METALWORKING PROCESSES AND EQUIPMENT PROGRAM

by N. E. Promisel

A previous speaker has described the scope, objectives and general organization of the Metalworking Processes and Equipment Program. Essentially, in this paper I want to describe to you in greater detail some specific examples of the phenomena and metal behavior which we think must be considered in looking ahead to new processing techniques and new equipment.

Let me remind you first of two basic features of this program: The first point is that our objective is to develop techniques and equipment which are adjusted to the characteristic behavior of the material, instead of trying to modify the material to be "workable" in equipment or under conditions which have been developed for something else. It is not reasonable to expect to be able to roll most efficiently refractory metals like tungsten or some niobium alloys on rolling mills designed for rolling mild steel. The forces, temperatures, speeds, strain rates, etc. required for efficient processing are entirely different in both cases. Too often, a newly developed alloy has been deliberately made "weaker" because it could not be processed by conventional techniques. Unless we take a giant step forward, we can expect the situation to get worse, because so much effort is now being spent to deliberately develop materials which resist deformation at higher stresses, at higher temperatures for longer times, etc. Obviously, we must develop techniques and equipment which permit processing these materials without sacrificing this greater resistance to deformation in service.

The second feature of this program that I would recall to you is this. Since we are attempting to hold to a minimum any change in the material for the purpose of easing its processing, but which could be detrimental in other respects, it is necessary to examine thoroughly and basically the deformation characteristics of

the material and new concepts or phenomena which might help in designing new equipment and new conditions for processing. Fortunately, there has been considerable research work on metal deformation phenomena and we have many new tools to help us. Figure 1 lists some of these in which there are very interesting and even exciting possibilities. There is opportunity to refer to only some of these in this rather limited paper, but these are the kinds of things I plan to discuss; namely, the research and development work described by the previous speaker as Phase 2 of this program.

It is evidently not easy to identify all the necessary subjects for study and to take into account all the work that is going on in this field. It is for this reason, as mentioned by the previous speaker, that a broad and comprehensive organization is important and has been established to assist in this program. Figure 2 is an early outline of the organization, as it affects the U.S. Navy program.

Now let us look more specifically at some of these effects, starting with certain ultrasonic phenomena. In 1955, Blaha and Langenecker discovered a softening effect in zinc single crystals that were exposed to the influence of ultrasonic waves. They attached an ultrasonic transducer to the end of a tensile specimen and recorded stress strain characteristics. The result was a drop in apparent yield stress while the specimen was under the influence of the ultrasonic waves. Dr. Langenecker is now at one of the Navy laboratories in California and has repeated similar tests using single crystal aluminum and polycrystalline stainless steel and beryllium. Some results are shown in Figure 3. It will be noticed that the stress necessary, in stainless steel and beryllium, to achieve a certain percentage elongation drops very markedly as the ultrasonic energy is increased from zero up to about 600 watts per square inch. In Figure 4, there is a similar drop for aluminum. This drop in the stress strain curve can also be achieved by increasing the temperature at which the specimen is tested without ultrasonic vibrations as shown in the right hand side of the figure, but if we calculate the energy necessary to achieve this drop in yield stress by using heat and compare it with the estimated energy to achieve the same result using ultrasonic energy, the latter is sufficiently less to suggest a very definite effect from the ultrasonic waves themselves, independent of any temperature effects which might have resulted. This observation has been confirmed on tungsten where the difference between heat and vibrational energies for the same results is much greater. It is believed that this effect is due to the activation of dislocations by the ultrasonic energy, in their dissipation of the ultrasonic waves, permitting them to move under very small applied stresses, certainly smaller than would normally be necessary for the indicated amount of plastic deformation.

This reduction in yield stress could be very important in design of new equipment for metal processing. A reduction in the force necessary for a certain degree of deformation should make possible some major reductions in the equipment size, for example in rolling wide sheet or the rolling of very difficult alloys.

Although this is very encouraging, nevertheless we should not overlook some serious problems, such as the means for introducing ultrasonic energy into the work and properly controlling it. However, the attractiveness of this possibility in the design of new equipment is such that we are vigorously pursuing this phenomenon. In fact, some tests are now being run in a very small experimental rolling mill.

Another advantage of using ultrasonic vibration in metal working is the reduction of frictional forces. Tube drawing experiments have been run. Figure 5 shows results for copper, using hydraulic force to give a constant drawing rate. The decrease in drawing force when the ultrasonic power was applied is very marked. In Figure 6, a dead weight was used to obtain a constant drawing force for copper and zircalloy tubing. Here the increase in drawing rate is very notice-able. The implication of these data is that much heavier reductions per pass can be obtained using ultrasonics, since the mechanical properties of the final tubing are not affected. In fact, advantage is already being taken of this in industry for small diameter tubing. A free bonus is the impressive improvement in interior surface finish of aluminum tubing, due to reduction in friction by drawing the tubing over a vibrating mandrel. Ultrasonic vibration also has advantages in other forming operations; for example, in reducing forming forces and, in the case of die forming, filling the dies better. Figure 7 shows a curled tube cross-section, using only half the normal force.

Of course, there are some limitations to the advantages of using ultrasonic vibrations for reducing friction. For example, the biggest improvements are at very slow drawing speeds, and as the drawing speed increases the advantage of using vibrated dies decreases. Also, it might well be that with the use of the proper lubricants and the proper die design we might obtain just as effective results even more practically. However, it is important to recognize that we have in ultrasonic vibrations an additional tool in metal processing; for example where the use of lubricants might prove to be difficult to use at high temperatures, ultrasonics could be effective.

Effect of ultra high pressures

Bridgman appears to have been the first person to have investigated quan-titatively the effect of pressure on the tensile properties of materials. He showed, with others, that the log of the reduction in area was a linear function of pressure, the equation* containing only two constants which could be readily determined, at

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* $\text{Log} \dfrac{\text{original area}}{\text{final area}} = C_1 + C_2 P$

least approximately. This equation has been confirmed for steels and for some aluminum alloys but does not appear to be true for all metals. For example, brass appears to gain little in ductility above about 90,000 psi. In tests on polycrystalline zinc, Pugh observed what appeared to be a transition pressure of about 8,000 to 12,000 psi below which reductions of area were less than 10% and above which the reductions of area approached 100%; that is, there was by no means a smooth linear relationship here.

Figure 8 shows tensile tests of pressed and sintered tungsten. The specimen on the extreme right shows the normal brittle tensile fracture at room temperature and pressure. At the extreme left is a ductile fracture when a hydrostatic pressure of 250,000 psi was used during testing, and in the center is a specimen which did not break when pulled to the capacity of the equipment under a pressure 350,000 psi but which showed considerable ductility. Polycrystalline tungsten seemed to remain brittle at room temperature up to pressures of about 110,000 psi. Above this amount it should be possible to deform tungsten a significant amount depending on the value of the pressure surrounding it. Figure 9 shows similar results of room temperature compression tests on small cylinders of beryllium. On the right hand side the edge cracking when the tests were run at atmospheric pressure can readily be seen. On the left hand side are the results obtained when the same amount of compression was performed under a fluid pressure of 150,000 psi and it is evident that there is considerable less edge cracking if any, thus indicating much greater ductility of the beryllium under pressure.

The results which I have just described on the impressive increase in deformability of tungsten and beryllium, confirmed by rather extensive tests on a variety of other metals, open up a very fruitful avenue for improving metalworking processes. It is worth noting that in those processes where the metal is actually being deformed under high pressures, due to the mechanical constraints and forces imposed on it, the metal's properties may well be different from those we measure in the laboratory at atmospheric pressure, and therefore these laboratory properties cannot be safely used to predict deformation during processing.

Fluid to fluid extrusion

Some very interesting work has been done in extrusion by substituting for the conventional ram a high fluid pressure, and forcing the material through the die into a lower fluid pressure container. This approach is shown schematically in Figure 10. Although this process has certain inherent problems such as the compatibility of the pressure fluids with temperature, this approach has the advantages of a considerable reduction in friction both in the die and on the cylinder

walls, the ability to minimize hoop tension forces on the die because of the counterbalancing hydrostatic forces, and the opportunity to modify the process by extruding from a very high pressure fluid into a lower pressure environment which nevertheless is still relatively high. In the diagramatic sketch of Figure 10, the receiving area which is marked as being at low pressure (p) is nevertheless above atmospheric pressure, even as high as a few hundred thousand pounds per square inch.

The work done thus far on this type of fluid extrusion has been limited to fairly small pieces, approximately two inches in diameter, but there does not seem to be any basic limitation on the process, other than the cost and difficulty of making high pressure equipment of the proper size. Pressures up to now have varied from less than 40,000 psi to about 450,000 psi maximum chamber pressure.

Figure 11 illustrates the results of tests of this type of extrusion on TZM molybdenum alloy which was deliberately recrystallized before extrusion, thus increasing the expected difficulty for good extrusion. The cracked specimen in the lower part of the figure was obtained by extruding into an atmospheric pressure zone. The uncracked specimen on top, which received the same 22% reduction was extruded into a receiver fluid at 40,000 psi. Tests on a sintered tungsten rod also gave a very sound extrusion at 14% reduction when the receiver pressure was raised to 150,000 to 200,000 psi.

Texture

It is readily recognized that mechanical properties of metals and alloys can vary very markedly with crystal orientation. This certainly is the case in most hexagonal crystalline metals, where the anisotropy in mechanical properties is generally considerable, and this is likely also in some of the cubic systems. Therefore, crystal orientation and texture generally can be expected to be very important considerations in metal processing.

An example of the effect of crystal orientation may be found in the study of single crystals of beryllium. At room temperature and pressure, there are just three modes of deformation for the beryllium, as seen in Figure 12: slip on the basal (0001) and prism (1010) planes; and twinning on the (1012) plane. It should be noted that both of the slip directions are perpendicular to the "c" axis of the crystal; thus there is no extension along that axis. The twinning mode does give a minor change in length along the "c" axis but requires a lateral displacement to do so. In studies of the effect of even traces of impurities on the strength

and ductility of beryllium, a very great improvement in elongation as a result of basal slip was obtained by zone refining a single crystal until a very high degree of purity was obtained. Figure 13 shows the increasing elongations obtained as the purity was increased by increasing the number of zone refining passes. Corresponding reductions of the critical shear stress on the basal plane are also seen on this figure. In Figure 14 there is illustrated a tensile failure of a pure single crystal of beryllium with the basal plane oriented originally at about 40º to the longitudinal axis of the specimen. One could certainly expect that there should be little fabrication difficulty with a material that appears to be so ductile, i.e. with this high degree of elongation.

However, tests have been run on this apparently "ductile" material by loading single crystals in compression perpendicular to the basal plane. The results gave no evidence of plastic flow, and the stress level in both cases in these tests reached about 285,000 psi before the specimen shattered and flew in all directions. Yet in tension, this material showed 140% elongation! However, such results are not really surprising when one recalls that there is no slip mode that exists along the "c" direction at room temperature and recalling that the twinning mode is restrained by the lateral constraint of the faces of the die.

While this illustration may seem somewhat extreme, it does illustrate the importance of orientation and texture in deformation processes and the danger of generalizing or extrapolating from just limited tests.

Superplasticity

A fascinating phenomenon that might prove to be very important in new concepts of metal deformation has to do with the unusual and often contradictory changes in plasticity that occur under conditions associated with structural changes in the atomic lattice such as phase changes and certain order-disorder reactions, presumably associated with the temporary breaking of atomic bonds. No effect is noted if there is no change in lattice parameter and conversely the greatest elongations correspond to the greatest changes in lattice parameter. A classic example is some work done by Sauveur in the torsion testing of iron over a temperature range of 600-1200º C. This may well be the earliest work representative of this phenomenon. Sauver and others since him found a relatively sharp increase in ductility near the gamma to alpha transition as the temperature decreased. Fig. 15 illustrates this phenomenon in the form of Sauveur's torsion results. A series of iron bars was heated at the centers to the temperatures indicated and simultaneously twisted in torsion. Obviously, when the temperature was high enough at the center, considerable ductility was shown as indicated by the twists in the bars.

However, at certain lower temperature areas along the bars, there was just as much ductility if not more than at the center or point of maximum temperature. These zones correspond to the Ar_3 temperature for that material. It will be seen that between the center of the bar and the Ar_3 zones there is not the same ductility, even though the temperatures were sometimes higher than those of the Ar_3 zones. In other words, where the phase change was taking place, an unusual degree of ductility was observed. Figure 16 illustrates this phenomenon in more recent work. Here a low carbon steel bar was loaded in tension at a relatively low load, corresponding to 400 psi. When the center of the bar was cycled form 800 to $1000 \degree C$ so that parts of the bar reached the critical temperature corresponding to the phase change, unusual elongations were observed at these areas as compared with the center of the bar where the temperature was actually higher, but too high for a phase change. This change in elongation is shown on the two curves.

This ductility phenomenon, referred to for convenience as superplasticity, has been studied in Russia extensively for about the last twenty years. The most dramatic and spectacular elongation in some of this Russian work was obtained with aluminum-zinc alloys near the eutectoid composition (80% zinc) at $275 \degree C$, where elongations of about 650% were found without failure taking place. It is evident that there exists a number of conditions in many alloy systems where there is very low resistance to deformation and where one can find an extremely high degree of plasticity, beyond that expected for the material even at much higher temperatures. Besides the systems already mentioned, the phenomenon has been found near the phase boundary of nickel alloys with chromium, copper, and in various other aluminum systems, magnesium systems, copper zinc systems, copper-nickel systems and others.

There is by no means agreement on a good explanation for superplasticity that fits all the observed data or even agreement on a good definition of superplasticity. Evidently, the phenomenon is related to a distortion of the atomic lattice under the application of stress, the availability of a metastable structure for subsequent stressing, and the weakening of the interatomic bonds that takes place during the reconstruction of the crystal lattice, as the alloy achieves a state of equilibrium. One dislocation mechanism to explain some of these observations, by Porter and Rosenthal, suggests that piled-up dislocations at grain boundaries and at other barriers produce stress fields which result in increased rate of nucleation. When the nucleus starts growing, the advancing interphase provides a sink for the piled-up dislocations resulting in observable plastic deformation. This suggested mechanism explains some observations but certainly not all. However, as further work continues in an attempt to derive explanations in terms of vacancies, dislocations, crystal structure, etc., it is hoped that the phenomenon itself may become useful in the development of new deformation processes.

Conclusion

In concluding my remarks on our metalworking processes and equipment program, I would like to point out that the examples which I have given of a variety of factors, from ultrasonics through superplasticity, merely represent examples of a considerable body of knowledge which exists in the literature and represents a tremendous amount of work still continuing on the behavior of metals, which we hope can be taken into account in developing new processes and new equipment. One of the main features of this program is the complete freedom to try to adopt any new concept and any new metallurgical phenomenon to the design of new equipment or to the development of a new technique. It is difficult, of course, to predict with any certainty the results of a program such as this. However, although this program was started primarily to permit practical processing of difficult materials which, almost by definition, are hard to deform, it seems clear to me that if we are successful in this objective, there is also a good likelihood that we will have developed techniques and equipment which are cheaper, simpler, more productive or otherwise have advantages even for the more common metals. It is hoped that by distributing the information from this program, widely, in the form of reports and publications, there will be stimulation for many to try to apply this information to new equipment. It is conceivable, therefore, that in years to come there could grow up a different kind of processing industry which could have a significant effect on the economy, not only of metal working, but on the final metal products themselves, and in turn these could involve large sections of a country's activities --the industrial organizations, the material producers, the fabricators, the equipment builders. Where big investments in capital equipment do not already exist, there would seem to be particularly good opportunities to take advantage of new concepts and new developments. One could hope, also, that these practical applications would in turn inspire further studies in science and technology, thus furnishing that productive exchange between science and engineering application which all of us are trying to achieve.

Acknowledgment

It has already been stated in this paper that one of the precepts of this program was the conclusion that there existed considerable data, and descriptions of a multiplicity of phenomena, which were, in essence, awaiting application to metal working process improvement. I have drawn freely, therefore, not only from investigations generated by the U.S. Navy, but from many others sources and reviews too numerous to list by detailed references. Included, for example, were Langenecker, Robinson, Eridgman, Bobrowski, Herman, Kaufman, Under-

wood, Rathenau, Sauveur, Sherby, Kearns.--to mention only some by name. To all of these sources of data and information I give grateful acknowledgment.

DEFORMATION CONSIDERATIONS

ULTRASONIC EFFECTS
FRICTION, WEAR, AND SURFACE–
    EFFECT STUDIES
HIGH–PRESSURE EFFECTS
DEFORMATION MODES
ORIENTATION AND TEXTURE
    STUDIES
STRAIN–RATE TEMPERATURE
SUPERPLASTICITY

Fig. 1   New tools for metal deformation.

METAL-WORKING PROCESSES AND EQUIPMENT PROGRAM
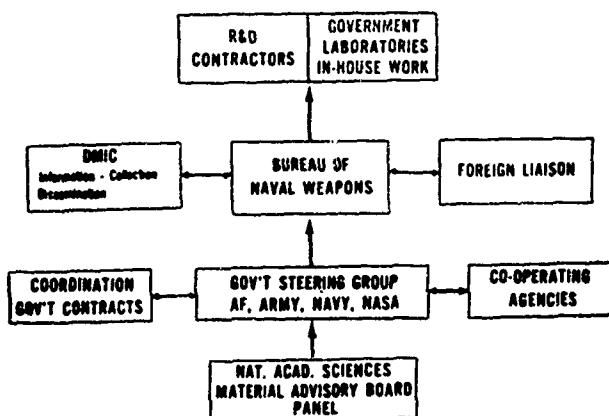
Fig. 2   Early outline of the Organization as
it affects the U.S. Navy Program.
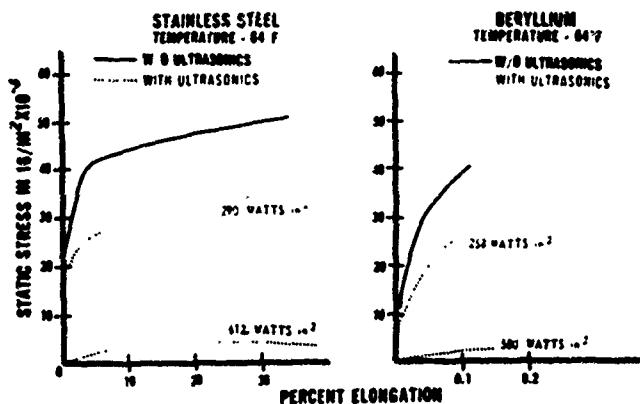
Fig. 3   Effect of ultrasonics on the yield stress
of polycrystalline stainless and Beryllium.
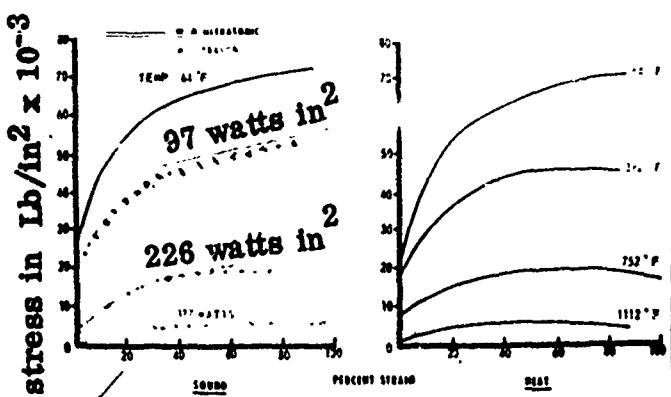
Fig. 4 Room temperature deformation of aluminum under influence of ultrasonics vs. deformation without ultrasonic activation at elevated temperatures.

ULTRASONIC TUBE DRAWING - COPPER

Hydraulic Draw Bench - 20 KC/sec.

Dimensions-inches				Percent Area Reduction	Ultrasonic Power Level Watts (Input)	Force lbs. (Drawing)	Rate in./min.	Percent Force Reduction
Initial		Final						
O.D.	Wall	O.D.	Wall					
0.313	0.032	0.225	0.019	57	0	1800	15	-
					500	815	15	55
					1000	686	15	68
0.313	0.032	0.275	0.032	13	0	1950	60	-
					1000	815		43
0.375	0.032	0.225	0.019	50	0	1260	60	47
					1000	725		

Aeroprojects, Inc.

Fig. 5 Tube drawing experiments for Cooper under constant drawing rate.

ULTRASONIC TUBE DRAWING - COPPER AND ZIRCALOY-2

Deadweight Drawing Apparatus - 20 KC/sec.
Ultrasonic Power Level - 1000 Watts.

Material	Dimensions-inches				Percent Area Reduction	Condition	Draw Force lbs.	Rate in./min.
	Initial		Final					
	O.D.	Wall	O.D.	Wall				
	0.313	0.032	0.275	0.032	13	Control	410	217
						Ultrasonics	410	2880
Copper	0.313	0.032	0.250	0.0315	24	Control	395	0
						Ultrasonics	395	7.5
	0.275	0.032	0.250	0.0315	12	Control	616	0
						Ultrasonics	620	171
Zircaloy-2	0.250	0.023	0.225	0.023	19	Control	870	0.25
						Ultrasonics	1000	36

Aeroprojects, Inc.

Fig. 6 Tube drawing experiments for Cooper under constant drawing force.

. 7 F.ects of ultrasonics on Die Forming.

Fig. Ton.   is n presses and sintered Tungsten.

9   Eff cts of high pressure on the deformation
havior of Bery lium.
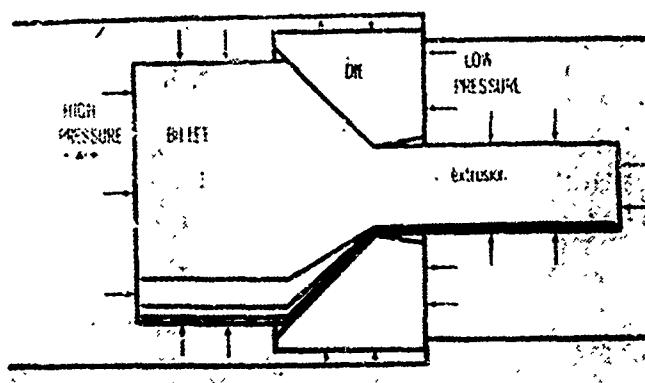
Fig. 10 Sketch of the set up for fluid to fluid extrusion.
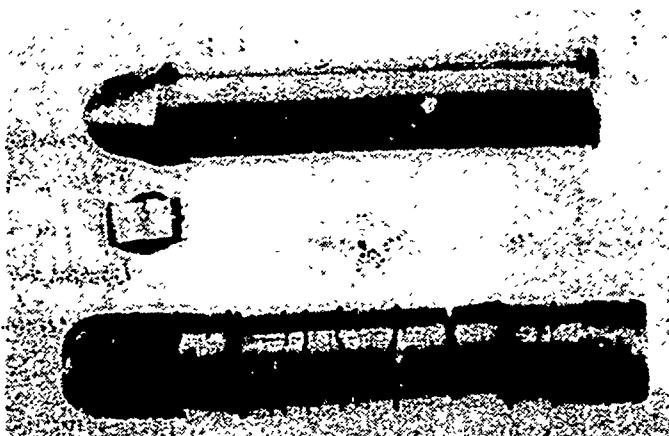
Fig. 11 Results of fluid to fluid extrusion on TZM Molybdenum.
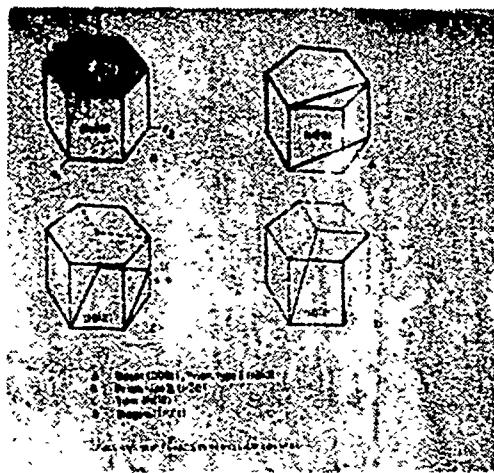
Fig. 12 Deformation Modes for Beryllium single crystals.

TENSILE TESTS OF ZONE REFINED BERYLLIUM CRYSTALS

Angle Between Axis and Basal Plane	No. of Passes	Deformation Mode	Elongation			Critical Stress Kgr. cm^{-2}
45°	Ref. melted Crystals	Basal	1	1	-	2500
45°	2	Basal	8.0	8.1	18	1750
45°	8	Basal	50.2	100	160	500

Fig. 13 Effect of purity on the elongation on critical shear stress
of Beryllium single crystals.

Fig. 14 Tensile failure of a pure single crystal of Beryllium.
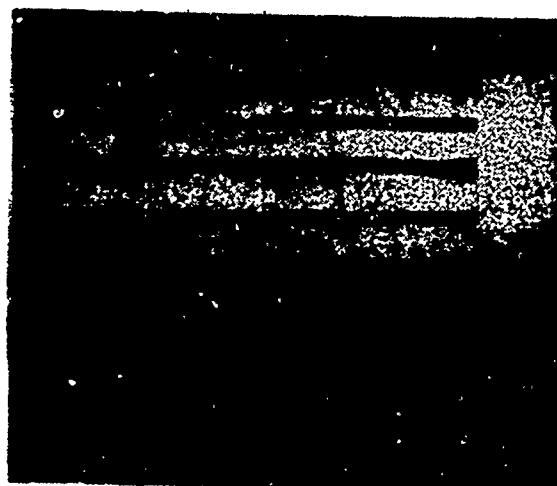
Fig. 15 Sauveur's Torsion results.
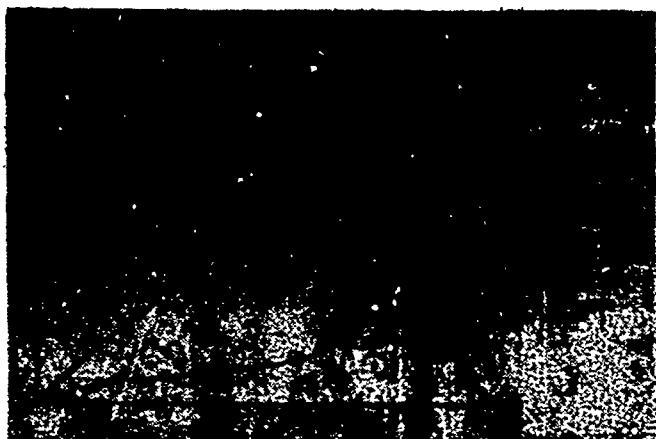
Fig. 16 Superplasticity of Iron with 0,03% Carbon.

MATERIALS RESEARCH IN SUPPORT OF ADVANCED TECHNOLOGY

by S. Valencia and P.A.G. Carbonaro

Introduction

The United States Army maintains an active research program to improve existing materials and to develop new materials. Advanced technology is fundamental for developing optimum materials which can be applied economically in military components.

Current trends of weaponry call for lighter weights, more intricate designs, higher strengths, greater toughness, and, for certain applications, resistance to high temperatures. These requirements, coupled with increasing labor costs, make research essential. Not only is such research necessary, but there is a need for the simultaneous accumulation of engineering data on new materials emerging from the research laboratories. When a new production technique is suggested for economic consideration, the effect of the new processing technology on engineering properties must be determined before that technique is qualified for productive purposes.

The United States Army Materials Research Agency, located at Watertown, Massachusetts, has a responsibility for the over-all broad Army program on materials research. This paper covers the following selected areas of interest:

a.   High-Strength Steel Castings

b. Precision Forming Techniques - Cold Swaging

c. Sub-Fusion Temperature Bonding

d. High Energy Rate Forging

e. Metal Removal

These processes augment rather than replace existing metal-shaping techniques and, when properly applied, produce highly superior products. However, it must be cautioned that before the processes are adopted, a study should be made to determine if they are practical and economical.

High-strength steel castings

Shape castings play an important role in weapon components because they lend themselves to intricate designs and offer great economic incentives over shapes fabricated by competing methods. In recent years, with the achievement of ultra-high strengths in steels, there has been an apparent need[1,2] for upgrading the technology associated with the production of shapes from these high-strength steels. Accordingly, there has been a steady effort in the area of metals research directed at obtaining a better understanding of the fundamentals involved in the production of a cast shape. Increasing the basic knowledge in solidification of high-strength steels, fluid flow, mold-metal reactions, response to thermal treatment, etc., would provide a firm basis for the design and processing of military castings.

Two important areas of immediate consideration were determined by the United States Army Materials Research Agency to be melting and refining, and solidification. Melting and refining determines inherent metal quality, while the manner in which metal solidifies determines the size and distribution of the grain.

It is generally recognized that sulfur content is an important influencing element in steels. The greater the sulfur content, the poorer the mechanical properties since the sulfur tends to segregate during solidification. Because of this tendency, the effect would be more pronounced with a cast shape than with a forged structure. Standard methods of desulfurization employing a double slag basic arc furnace procedure[3] were investigated as well as rapid desulfurization techniques[4] that can be conveniently employed on small, experimental induction-melted heats. The results of these investigations are graphically illustrated in Figures 1 and 2.

In Figure 1 the ductility and toughness of arc furnace steels at constant strength levels are plotted against sulfur content. Improvement in ductility and toughness can be readily seen as the sulfur content decreases. Whereas in forged steels sulfur content below 0.025 percent is of little concern, in the case of steel castings there is a direct proportional increase in ductility with decrease in sulfur content even with comparatively small amounts (0.010 percent) of sulfur. The effect of sulfur upon the mechanical properties becomes even more pronounced at the ultra-high strength levels.

Figure 2 shows, in bar-graph form, the effect of sulfur content on steels at the tensile strength range of 275,000 to 300,000 psi. Silicon-modified 4340 steels at extremely low sulfur levels were compared with similar steels at the 0.017 percent level. The basic analyses and heat treatments were the same, and yet by decreasing the sulfur content there was as much as a twofold increase in ductility which is attributed directly to the decrease in sulfur content. The data in both Figures 1 and 2 represent results of controlled experiments where the sulfur content was the only variable.

This type of data, combined with similar results from other engineering laboratories and foundries, made possible the establishment of a specification for high-strength steel casting, MIL-S-46052 dated 28 September 1962. This specification, entitled "Steel Castings, High Strength, Low Alloy", cites the following combination of properties for high-strength castings:

MECHANICAL PROPERTIES, MINIMUM

Class	Tensile Strength (psi)	Yield Strength 0.2% Offset (psi)	Reduction of Area (%)	Charpy V-Notch Impact Energy at -40 C (ft-lb)
180 - 150	180,000	150,000	20.0	15
220 - 180	220,000	180,000	15.0	12
260 - 210	260,000	210,000	6.0	9

With this limited but significant amount of work directed toward upgrading the melt quality, research effort was then increased in the area of solidification.

Solidification Research

The vulnerability of high-strength steels to metallurgical size effect has been established but the exact cause for this effect has been the basis for a continuing study program. The effect could be due to grain size, nonmetallic inclusions (size and distribution), microporosity microsegregation, or a combination of these variables. Studies of these variables have been underway at a number of laboratories and universities[5,6,7] under Department of the Army sponsorship.

Of particular interest in this general area of solidification research has been the study of dendrites, their formation and character.

Laboratory test ingots of silicon-modified AISI 4340 steel were cast in such a manner as to provide a predetermined dendritic pattern. A typical test ingot is cylindrical, about 8 inches in diameter and 10 inches high, cooled so that dendritic structure will vary, giving the researcher columnar as well as equiaxed dendrites for study. Figure 3 shows a macrostructure of a transverse disk from such a test ingot. The structure was developed by etching in a solution of 38 percent hydrochloric acid, 12 percent sulfuric acid, and 50 percent water for 15 minutes at 170 F. The macrostructure contained a typical columnar zone in the outer portion with an equiaxed structure in the center portion.

The dendrites shown in Figure 4 were subjected to a variety of laboratory tests to determine microporosity, inclusions, and information on the extent of microsegregation within and at the boundaries of the dendrites. With the aid of an electron-beam analyzer it was possible to obtain quantitative chemical analyses of very small portions (1-1/2 microns in diameter) on the sample. By taking a series of analyses across a scan (a given distance), one can directly measure the change in chemical composition across dendritic arms. The size of a dendritic arm varies in the order of magnitude from 10 to 1000 microns and a rather complete analysis can be obtained from such a cross-scan distance. The only practical limitation for this technique is that quantitative chemical analysis cannot be obtained for elements below magnesium in atomic weight. Thus in the case of steel one cannot analyze for carbon, phosphorus, and sulfur, but all other elements of interest can be determined with the help of the probe. Typical results of the probe analysis are shown in Figures 5, 6 and 7 which indicate that conventional high temperature homogenization treatments have little effect on the diffusion of the segregated elements.

Future Requirements

Obviously any technique which may be generated to reduce the degree and size of segregation will enhance the over-all properties of the cast shape. In other studies the effect of size and type of dendritic structure is being scrutinized since the control of dendritic pattern within a cast shape will largely control the distribution of segregated areas. If the combination of properties listed below can be obtained as a result of this research program by establishing the necessary technology for actual manufacture, then the economical advantage is obvious for the production of complex military shapes.

Limitations to the wider use of high-strength steel cast shapes is primarily associated with current knowledge in the field, and the type of research described is required to establish the necessary fundamentals for ultimately advancing the state-of-the-art through new technology.

TARGET PROPERTIES FOR HIGH-STRENGTH,
TOUGH, SHAPED STEEL CASTINGS

Max. Crit. Section Size (in.)	Yield Strength 0.2% Offset (psi)	Reduction of Area (%)	Elongation (%)	Charpy V-Notch Impact Energy at -40 F (ft -lb)
	160,000 - 169,999	25	14	24
3	170,000 - 179,999	24	13	22
	180,000 - 189,999	23	12	20
	190,000 - 199,999	22	11	19
2	200,000 - 209,999	21	10	18
	210,000 - 219,999	20	9	17
	220,000 - 229,999	19	8	16
1	230,000 - 239,999	18	7	15
	240,000 - 249,999	17	6	14

Precision forming techniques - Cold Swaging

In another area, generally identified as "precision forming", the United States Army has been investigating comparatively new and modified processes which will yield a product requiring little or no machining in manufacture. The new precision-forming technique discussed herein is a further development of the well-known swaging process. This process was selected for investigation in an attempt to develop new techniques, not only to meet more exacting requirements and to produce a higher quality product, but also to offset labor costs. This particular process consists of the plastic reshaping of tubular workpieces by means of high pulsating pressure applications produced by rotating hammer dies. While the outside diameter of the tubular workpiece is being reduced, varied internal contours (such as splines) can be produced by introducing into the inside of the workpiece a contour mandrel whose shape can be reproduced on the inside of the tubular workpiece.

As part of a program sponsored by the United States Army for the development and application of the technique, a contract was negotiated with a commercial facility to design, develop, and construct a cold-swaging machine capable of producing intricate internal contours within cylindrical components. The resulting machine tool which is shown in Figure 8 was installed at the United States Army Materials Research Agency. The machine is composed of two main units: (1) the actual hammering unit known as the "head", and (2) the feeding unit known as the "slide".

The head contains the swaging mechanism which consists of all the components necessary to complete the hammering operation. The schematic drawings in Figures 9 and 10 show the main components of the head with the hammers in the closed and open positions. The shaft, in which the four hammers are located crosswise, is actuated by means of a 40-hp motor over a flywheel which is connected to the motor by V-belts.

The twelve rollers, equally spaced through the roller cage, are equipped at both ends of the rollers with a spacer ring. Spring power and centrifugal force effect a steady contact between the sinusoidal back surface of the hammers and one roller, and between the surface of the rollers and the liner. When the machine is in operation, the shaft rotates rapidly, at approximately 250 rpm. As a result of this rotation of the shaft, the hammers with their curved backs pass over the rollers, thus exerting a powerful squeezing action on the workpiece through the swaging dies. All hammers work simultaneously and the stroke is given by the high point of the sine curve on the back of each hammer. The hammers apply approximately 2000 blows per minute. Interchangeable dies may be used to permit the processing of tube sizes ranging from 1/2 inch to 3 inches outside diameter.

The slide contains the workpiece feeding mechanism which consists of a double screw drive with adjustable nuts. The screws actuate the slide carriage in which the freely rotating push rod supporting the workpiece is installed. The screws are driven by a Vari-Motor drive and chain drive over a cross-connected train of gears. This train of gears has two speed ratios and a special forward and reverse quick-feed gear. The feeding speed can be set to vary from 5 to 100 ipm. The slide is capable of feeding a workpiece with a maximum length of 60 inches and a maximum feed load of 40 tons.

Besides the head and the slide just described, the machine is equipped with a mandrel drive and a back pressure attachment. The mandrel drive is used to carry out all the movements necessary for the mandrel during the swaging operation and the back pressure attachment is required to guide and keep the workpiece

centered during swaging and to eject the work upon completion.

Applications

Examples of applications which have been under investigation at the United States Army Materials Research Agency are: (1) rifling of small arms, and (2) forming of both chamber and rifling of small arms in one operation.

Rifling Investigations

Typical of the investigations which have been conducted is the rifling of .30 caliber rifle barrels. The material used for the blanks was SAE 4150 steel heat treated to a R_c32. The starting tubular workpiece used for these investigations were 1.350 inches outside diameter (O.D.), 0.348 inch inside diameter (I.D.), and 30 inches long. Figure 11 shows the dimensions of the workpiece prior to swaging, the rifled barrel after swaging, and the mandrel used for rifling. Based on these dimensions, the percentage reduction and elongation obtained was 14 percent. These tests have proved that the new technique can hold close tolerances and produce good surface finishes. As shown in Figure 11, the inside diameters have been held to within 0.0005 inch on the .30 caliber rifle barrels. In addition, the surface finish was improved from 75 microinches to an average of 8 microinches. Finally, the swaging speeds for these tests have been in the range of 10 to 15 ipm. Experiments have also been conducted with the rifling of .60 caliber and 20mm rifle barrels and the results have been successful.

Swaging of Chamber and Rifling of Small Arms

In addition to the rifling tests, successful experiments have been conducted recently which include the swaging of both the chamber and the rifling of .30 caliber rifle barrels in one operation. The dimensions of the starting tubular workpieces used for these experiments were 1.350 inches O.D., 0.348 inches I.D., a length of 23 inches and a counterbore of 0.472 inch I.D. with a depth of 1.770 inches. Figure 12 shows the workpiece prior to swaging, the dimensions of the chamber and rifling after the swaging operation, and the mandrel tool employed. The chambering and rifling mandrel is a two-component tool joined in the manner shown by the drawing.

During the swaging of the chamber portion, both chamber and rifling mandrels travel forward together with the workpieces. Immediately upon completion of the chamber portion, the chamber mandrel separates from the rifling mandrel and continues travelling forward with the workpiece while the rifling mandrel is automatically locked in place within the throat of the dies and from then on cannot travel forward, although it remains free to rotate.

These experiments have further proved that the new technique can hold close tolerances and produce good surface finishes, and that both the chamber and rifling of small arms components can be formed by swaging.

Die Design

As must be expected, die shape for swaging is extremely critical and the design illustrated in Figure 13 has been followed as closely as possible. The factors affecting and limiting die design are as follows:

Entrance Angle

The angle which the inlet end of the dies makes with the horizontal axis. This has been varied from 3º30' to 5º depending on the application.

Die Radius

The radius of the dies at the throat must be 6 to 8 percent more than the radius of the finished component.

Exit Angle

The angle which the exit end of the dies makes with the horizontal axis. This has been varied from 1º30' to 2º30'.

Die Material

Types of steels employed for the dies are listed as follows:

Type	C	Mn	Si	Cr	W	V	Mo
A	0.35	0.30	0.30	3.50	9.00	0.40	--
B	1.00	0.70	0.30	5.25	--	0.25	1.15

Die Hardness

All dies which have been employed have been heat treated to R_c63.

Die Lubrication

The lubrication and cooling of the dies is effected by a flange-mounted pump. This same oil system lubricates the hammers and the rollers. The oil being used is eight parts lubricating to one part cutting oil.

Mandrel Design

The mandrel, of course, plays a very important part in the operation. First of all, the mandrel determines the internal contour and the mandrel surface determines the surface finish on the inside of the tubular workpiece. The materials which have been used for the mandrels are tool steels which have been heat treated to an average hardness of R_c60.

Unique Advantages of Swaging

Advantages derived by the employment of this process are not limited to the close tolerances possible or the fine surface finish which can be obtained. The process holds waste of material to a minimum because metal is displaced instead of cut, and it reduces time on secondary operations to a minimum since only end trimming of parts is involved. Another particular advantage is the fact that the physical properties of material are improved by the cold working. Furthermore, since such a machine can be easily automated for all types of swaging jobs, the

process makes economically feasible the mass production of parts. Finally and perhaps the most significant advantage is the fact that in many instances swaging proves to be the only feasible method of manufacture.

Cost Comparison

Subsequent to the research and development work executed by the United States Army, several American manufacturers have produced improved versions of the United States Army-designed machine. These machines are now commercially available and some have already been installed at industrial plants. One of these machines is used by an automobile manufacturer for finishing the bore contours of starter motor clutch housings. Several commercial firearms manufacturers in the United States also use the swaging machine.

The operations usually involved in the conventional and the cold-swaging methods are:

Conventional		Cold Swaging	
1.	Deep hole drilling	1.	Deep hole drilling
2.	Ream bore	2.	Counter bore
3.	Broach rifle profile	3.	Swaging of chamber and
4.	Machine chamber		rifle profile
5.	Hand ream chamber		

The following cost comparison can be made to show the savings which are possible by using cold swaging instead of the conventional method. The cost information was supplied by a commercial firearms facility which has two machines in operation. The comparison does not include the costs involved in items such as reaming oil, rifle broaching oil, scrap material, etc., since they are not required for the cold-swaging method.

Operation	Conventional Method		Cold Swaging	
	Labor	Tooling	Labor	Tooling
Ream Bore	$ 3.36	$24.17	-	-
Broach Rifle Profile	3.46	6.17	-	-
Machine Chamber	3.64	9.88	1.25	1.90
Hand Ream Chamber	3.58	2.37	-	-
Cold Swaging	-	-	3.07	-
Rifle Mandrel	-	-	-	1.40
Chamber Mandrel	-	-	-	4.00
Set of Dies	-	-	-	5.00
Subtotals	$14.03	$42.59	$4.32	$12.30
Grand Totals	$56.62		$16.62	

Sub-Fusion temperature bonding

A third area under investigation in recent years is the sub-fusion temper-
ature or solid state bonding process for joining ultra-high-strength materials.
Most high-strength materials, particularly alpha and beta type titanium alloys,
are susceptible to severe embrittlement when bonded by the more common fusion
welding techniques. Since these materials may be adversely affected by the fusion
welding, this section covers an engineering study of one such material (a titanium
alloy) to determine the feasibility of fabricating large-diameter rocket motor
casings by solid state bonding. Preliminary tests were conducted with the titan... .1
alloy selected and subsequently the material was applied to a prototype component
since the test results indicated that the solid state bonding process could be em-
ployed. This study was executed by the United States Army Materials Research
Agency[8] in conjunction with two industrial facilities as a joint program.

Material

The high-strength material selected for the study was Ti-6Al-6V-2Sn alloy which is capable of being heat treated to a minimum (0.1% offset) uniaxial yield strength of 175,000 psi. The supplier's analysis of the material used in the experiment is as follows:

	Element (Weight %)									
Heat No.	C	N_2	C_2	Al	Sn	Fe	V	H	Cu	Ti
D-2001*	0.027	0.022	0.19	5.4	2.0	0.72	5.7	0.0045	0.68	Remainder
D-2003**	0.025	0.026	0.17	5.5	2.0	0.73	5.4	0.0035	0.67	Remainder

*D-2001 was used to form hemispherical end closures
**D-2003 was used to form cylindrical center sections

Preliminary Heat-Treatment Tests

In order to determine the most suitable heat treatment for the completed prototype component, specimens of the material were subjected to two different heat treatments as shown in Table I along with the resulting mechanical properties:

TABLE I   HEAT TREATMENT TEST DATA

Heat	Heat Treatment* (deg F)		Y.S. 0.1% (ksi)	T.S. (ksi)	Elong. (%)	R.A. (%)	Charpy V-Notch Impact Energy at -40 F (ft-lb)
	Solution Temp.	Aging Temp.					
2003	1630	1150	178.5	190.0	6.0	9.2	6.0
			179.0	190.5	9.0	15.5	5.7
2001	1 hr WQ	4 hr AC	177.0	186.0	5.5	10.6	6.7
			176.0	185.0	5.0	9.9	6.0
2003	1580	1100	181.5	192.0	5.5	12.2	6.4
			180.0	191.0	7.0	13.3	5.4
2001	1 hr WQ	4 hr AC	177.5	187.5	8.5	19.4	7.0
			175.0	186.0	6.0	9.9	7.3

*WQ = water quenched; AC = air cooled
Standard 0.252-inch-diameter tensile specimens (MIL-T.46038)
Standard 0.394-inch-square Charpy V-notch impact specimens (MIL-T-46038)

Preliminary Bond Evaluation Tests

Preparatory to fabricating the component, it was deemed necessary to conduct a number of experiments to establish the processing schedules for the actual forming operation and to conduct mechanical testing of the joint. The processing variables included (1) joint configuration; (2) surface finish; (3) heating media (oxyacetylene gas pressures); (4) loading pressures and cycle; (5) bonding time; and (6) degree of upset (hot gather). Tests were conducted on a test specimen, as shown in Figure 14, of similar configuration to the final component. The results of mechanical testing are contained in Table II, as received from the supplier.

TABLE II   MECHANICAL TEST DATA

Specimen	Specimen Diameter (in.)	Area (sq in.)	Ultimate Load (lb)	T. S. (ksi)	Elong.* (%)	R. A. (%)
1	0.2490	0.0487	8080	165.9	16	32.2
2	0.2505	0.0493	8240	167.1	15	31.0
3	0.2505	0.0493	8220	166.7	14	24.3
4	0.2505	0.0493	8040	163.1	14	29.8
5	0.2505	0.0493	8080	163.9	14	28.4
6	0.2505	0.0493	8020	162.7	14	29.0
7	0.2505	0.0493	8120	164.7	14	29.0
8	0.2505	0.0493	8100	164.3	15	29.0
9	0.2505	0.0493	8120	164.7	13	27.8
10	0.2490	0.0487	8100	166.3	11	19.1
11	0.2500	0.0491	8140	165.8	13	28.1
12	0.2495	0.0489	8200	167.7	12	30.5
Average				165.2	13.75	28.2

*0.5-inch gage length.
Standard 0.252-inch-diameter tensile specimens (see MIL-T.46038). All specimens were taken perpendicular to bonded interface.

Prototype Component Fabrication

After the preliminary tests were completed, fabrication of the prototype component proceeded. A cross-section view of the 22-inch-diameter cylinder is shown

in Figure 15. The end closure portions of the casing were hot hammer forged and the cylindrical center section was hot ring rolled. Prior to the joining operations, the cylindrical and the end closure sections were machined using accepted techniques for machining of titanium. The first step in the bonding operation consisted of placing one end closure and the center cylindrical section in the horizontal pressure bonding equipment shown in Figure 16. Joint interfaces were cleaned with ether and the components were butted together with the use of a force applied through the end closure and cylinder shoulders. The inside surfaces were protected from surface oxidation by means of purging gas. The joint was heated with an oxyacetylene flame ring to a temperature of approximately 1650 F in about 2 minutes. Figure 17 shows solid state bonded motor casing indicating pertinent items. A bonding pressure of 8000 psi was applied simultaneously with the heat, and plastic flow occurred as the preselected temperature was approached. The pressure was then dropped to 4000 psi and the bonding action was completed.

In order to bond the other end closure to the assembly, a similar cycle was repeated and a suitable bonding was effected. After bonding, the fabricated case was aged at 1100 F for one hour, followed by an air cool. Surfaces were finished by machining to the required dimensions indicated in Figure 15.

The fabricated case was then subjected to hydrostatic pressure and the test results were satisfactory. Final product is shown in Figure 18.

These experiments demonstrated that fabrication of large-diameter rocket motor casings by solid state bonding is feasible. It further demonstrates that with the use of such a process, high-strength alloys could be used with greater reliability by eliminating the adverse effects encountered in common fusion welding. In the particular case investigated, it would be impossible to fabricate the component by any other known method and, therefore, this process represents a new and economical industrial capability.

High energy rate forging

A fourth area of interest which the United States Army has been investigating[9] is the application of high energy to the forming of metals, ceramics, and other component materials. Here again, this new process was selected for investigation because it offers production and economic advantages.

This particular process consists of a metalworking machine that applies high rates of energy to materials by means of a pneumatic hydraulic system. The

energy source consists of an accumulator with stored high pressure gases which can be released practically instantaneously to actuate a piston that carries tooling to do useful work in compacting, forging, or extruding. The compressed gas drives the working piston at very high velocities.

Machine Tool

The high energy rate forging machine employed for the investigation discussed here is shown in Figure 19. This machine is one of several models developed and marketed by a commercial facility.

This forging process has two major systems: first, a power source or energy-producing section, and second, a reaction system to absorb the high forces that can be produced. A better explanation of how the process works can be given by describing the schematic shown in Figure 20. The driving section or power source consists of a simple cylinder divided into two chambers by means of an orifice plate (Figure 20). Riding in the lower portion of this cylinder (Chamber B) is a piston which carries the working tooling. This piston carries a sliding seal that acts on the inner wall of the cylinder portion of Chamber B. Attached to the upper face of the piston is a resilient seal.

To facilitate explanation of the operational features of this process, let it be assumed that the cylinder has an inside diameter of 3.5 inches and that the orifice plate has a hole 1 inch in diameter. Thus the cross-sectional area of the cylinder and the orifice would be approximately 10 square inches and 1 square inch, respectively. If Chamber B is pressurized with gas to 200 psi, neglecting the area of the ram, a net force of 2000 pounds is generated on the lower face of the piston. This force causes the piston to seal tightly against the orifice plate. Chamber A can now be pressurized to 2000 psi without causing movement of the piston assembly. In the ready position, the 2000 psi pressure acts on the exposed piston area of approximately 1 square inch. The system is now in equilibrium. If the pressure in Chamber A is increased slightly, a net force is generated against the piston causing it to move away from the orifice plate.

A slight displacement allows the 2000 psi pressure of Chamber A to act over the entire upper face of the piston, thereby producing a propelling force of 20,000 pounds in less than one millisecond. This propelling force, applied to the piston, produces instantaneous velocities of several hundred inches per second.

The piston is returned to its original firing position by pumping high pres-

sure oil into Chamber B, forcing the high pressure gas back into Chamber A, and reseating the upper face of the piston against the orifice plate. After the seal is made, the oil is bled from the system and low pressure gas (200 psi) maintains the piston in position; the system is again in equilibrium awaiting the next firing cycle.

The reaction system, essentially a simple combination hydraulic and pneumatic recoil mechanism, is required to compensate for the high forces that are produced. This system consists of two pistons attached to the tie rods of the frame riding in a cylinder section as shown in Figure 20. The recoil mechanism tends to maintain the machine in a predetermined position.

Application

Typical of the applications under investigation at the U.S. Army Materials Research Agency is the forming of a prototype component for the "Redeye" high-explosive case shown in Figure 21. To determine the feasibility of producing the component by the high energy rate process, experimental quantities were fabricated. The component is currently being formed by conventional upset forging techniques.

The forgings made by the high energy rate process were formed from 6Al-4V titanium alloy billets (2.830 inches in diameter and 1.750 inches in length) heated in air and forged from a temperature of 1750 F utilizing a fire pressure of 1000 psi. This pressure corresponds to an energy level of approximately 57,100 foot-pounds. A stroke of 10 inches was held constant for all forgings. A water-graphite mixture applied to the punch and die by means of a spray gun was used as a lubricant.

Tooling

To carry out the feasibility studies and at the same time have appropriate tooling for other types of research programs, a set of universal tooling was obtained. It was designed to allow for maximum versatility and can be used for closed cavity extrusion molding, forward extrusion, and forging of small components by interchanging the various die sections. The universal die holder is shown in Fig. 22.

A set of forging tools was designed and fabricated to form the component for the Redeye high-explosive case. The design of the die used in conjunction with the set of universal tooling incorporated a threaded section within the die cavity (see Figure 23) into which the forged material would flow and thereby lock itself within the die. This arrangement made it possible to strip the forging from the punch upon retraction of the ram. The forging (Figure 24) was then unscrewed from the cavity by means of a special tool designed to fit the two projections at the rim of the forged cup. These two projections are formed at the time the component is forged by means of depressions at the shoulder of the punch shown in Figure 25.

Cost Comparison

The following cost comparison can be made to show the savings which are possible by replacing the conventional upset forging method by the high energy rate process.

Items	Conventional Method	High Energy Rate Method
Forging Operation	$ 48.00	$ 96.00
Starting Workpiece	834.00	588.00
Totals	$882.00	$684.00
Savings per 100 units	$198.00	

The difference in the cost of the starting workpiece is based on the fact that 2.78 pounds of material are required for each item when produced by the conventional method and only 1.96 pounds are required per item for the high energy rate process. The cost of the titanium alloy for the comparison was assumed to be $3.00 per pound.

The difference in the cost of forging is based on the fact that two operators are required for the high energy rate process, whereas only one operator is required for the conventional upset forging method.

Advantages which can be derived from the employment of the high energy rate forming process are not limited to material savings. This process also offers economic benefits in the production of better parts with smoother finishes and finer grain structures. For some applications, this process enables the part to be forged in one operation, thereby reducing the time and tooling costs involved in secondary operations. Another particular advantage is the fact that even the most difficult refractory metals have proved malleable when subjected to the high velocity rates generated by this process. Finally, high energy rate forming provides an additional fabrication technique for the design engineer's consideration.

Metal removal

The last area of interest discussed here is the removal of metal at high velocity utilizing advanced ceramic cutting tool materials.

The critical supply of the materials commonly used for metal-cutting tools has always played an important role during periods of emergency. Difficulties in procuring tungsten carbide and high-speed tools during emergency periods indicated that it was mandatory to obtain a satisfactory nonstrategic cutting tool. Hard ceramic materials are available in abundant supply and can be used in place of tungsten carbide cutting tools and high-speed steel tools for some applications.

In view of the foregoing, the United States Army Materials Research Agency has been engaged in recent years in a continuing program designed for the advancement of the ceramic cutting tool in this country. The program has been carried out as a joint program between the United States Government, industry, and universities. Therefore, the following review of ceramic tools represents the result of a joint effort rather than the test results of any of the numerous projects carried on or sponsored by the United States Army.

Ceramic Tool Manufacture

At the present time, all ceramic cutting tools being produced in quantity

are manufactures from aluminum oxide.

The current methods of ceramic tool manufacturing are the cold-pressed and hot-pressed techniques. The cold-pressed technique consists of forming the powdered alumina under pressures of 40 to 60 ksi followed by sintering in an atmosphere-controlled furnace at temperatures of 1700 to 1950 F. The second technique consists of simultaneously applying heat and high pressure to the alumina powder in a graphite crucible or mold. The second is more expensive but it produces a cutting tool with better physical properties. In both techniques, grain growth inhibitors are added to avoid excessive grain growth which embrittles the material.

At this Agency all evaluation studies have been conducted on a 2-1/2-inch turret lathe equipped with a dynamometer and recording instrumentation as shown in Figure 26. This turret lathe has a maximum rotational speed of 2000 rpm actuated by a 35-hp drive motor, and is equipped with variable speed control. Speeds of approximately 3500 surface feet per minute can be obtained if a workpiece of suitable diameter is employed. Other cooperating facilities conducted engineering studies under simulated or actual production conditions and attained machining speeds of 7000 surface feet per minute. The ceramic test results generated with this Agency's machine, coupled with the test results from other laboratories, have improved the status of ceramic tools.

Tool Design

The most common type of ceramic tool is the disposable insert type (see Figure 27) which is produced in square, triangular, and circular shapes. The negative rake angle is generally preferred because the negative rake blank offers six to eight cutting edges, according to its particular shape. The positive rake square blank presents four cutting edges, and would, therefore, seem less economical.

A narrow negative land honed on the edge of the tool decreased the tendency of the tip to shear off. The nose radius should be as large as possible but small enough to prevent dangerous chatter and vibrations which shorten tool life.

Machining Test Results

Ceramics have proven successful in machining all materials except for certain high-temperature steels such as the high nickel alloys, and certain light metals such as aluminum and titanium. The high-temperature steels appear to be too hard and abrasive to machine effectively. The reason for the difficulty in machining light metals has not been clearly established by investigators.

There is very little tendency for "built-up edge" to develop in ceramic cutting because there is less material adhesion than with other tool materials. The appearance of the chips produced in ceramic operations (see Figure 28) is different from that of chips produced by other cutting tool materials.

Excellent workpiece surface finishes can be produced, particularly in the high-speed range. Workpiece and cutting tool remain cool provided the chip breaker is adjusted properly. Coolant is not generally used during machining.

Ceramic tool failure occurs either by a sudden catastrophic fracture of a large portion of the tool or by a wearing away of small particles. However, it must be pointed out that vibrations and interrupted cutting have deleterious effects on ceramic cutting-tool life. Under certain machining conditions, ceramics can perform at cutting speeds at least 100 percent greater than those used with carbides.

Production Problems

Although considerable experimentation has been carried out by industry, universities, and the United States Government, and ceramic tools have been tried on a number of machining applications, there are several problems which are currently inhibiting the universal use of ceramics in production application. One of these problems is the fact that specially trained operators are required for the successful application of ceramic tools. Another problem is directly related to machine tool requirements which are mandatory for attaining maximum efficiency in the utilization of ceramic cutting tools. In high-velocity machining, the speed of the machine must be correlated with adequate power supply. There is indicated a need for specially designed machine tools to take advantage of ceramic cutting tool techniques. Therefore, manufacturers who have decided to utilize ceramic cutting tools have had to make homemade additions to standard machine tools. Because of this, the production advantages gained from ultra-high machining speeds have been sacrificed.

Finally, the most important problem is that of economics. The cost of ceramic tools is at least twice that of high-grade carbides. Furthermore, ceramic tools with their negative rake angles and the higher speeds utilized in ceramic tool cutting require increased power consumption, resulting in higher costs.

Advantages

Ceramic cutting tools offer the following advantages:

1. Ceramic materials are readily available

2. Ceramic tools have a longer life due to high hardness at both room temperature and elevated temperature

3. Machining can be carried out at higher speeds thus decreasing machining time

4. No built-up edge is generated

5. Finish of workpiece is improved

General Remarks

Increased usage of ceramic tools is dependent on (a) greater familiarization by the tooling engineers, (b) specific application, (c) availability of adequate machine tools, and (d) economic consideration.

In the event of shortages of the more commonly employed cutting tool materials, ceramic tools will serve as a substitute material regardless of economic considerations.

Summary

As stated in the introduction, the areas of interest covered in this paper represent only a sample of the current United States Army Materials Research Agency programs.

The casting studies conducted to date indicate that even greater effort must be expended to obtain a more fundamental understanding of the variables associated with solidification. There is a need for advanced castings technology but this cannot be done without basic data. Therefore, current United States Army programs are oriented toward materials research.

The rifling of barrels by swaging promises to become an acceptable process after the current experimental techniques are perfected and the pilot plant studies are completed. Rifling now produced by broaching will show substantial cost savings when produced by swaging. Furthermore, the new technique will provide the design engineers more latitude since such a machine tool will make inner contours unobtainable by other methods.

The sub-fusion temperature bonding experiments have demonstrated that in some cases advanced technology makes it possible to successfully employ certain materials such as the high-strength titanium alloy used to fabricate rocket motor casings. Employment of the solid state bonding process eliminated the adverse effects encountered in common fusion welding. In fact, the prototype component under investigation would have been impossible to fabricate by any other known method.

The high energy rate application studies conducted to date, although limited in quantity, indicate that such a method of forming opens new design possibilities since the process offers versatile production capabilities. The process can be used to forge, extrude, compact, upset, or perform any similar forming operation. Furthermore, advantages which can be derived by utilizing the high energy rate forging process include better parts, smoother finishes, less metal loss, and simpler tooling. Another particular advantage is the fact that the technique makes it possible to process refractory metals which are difficult to form.

Finally, the work in ceramic cutting tools carried out at the United States Army Materials Research Agency has stimulated considerable interest in the ceramic cutting tool industry in this country. The work continues but its full acceptance still has many obstacles. There is a need for educational programs before ceramic tools can be fully incorporated in the production line. Furthermore, the development of more adequate machine tools is essential. Availability of specially trained personnel and improved machine tools should increase the use

of ceramics.

The selected areas covered in this paper confirm that research is essential. Continuing materials research will advance the technology necessary to develop optimum materials for economical application of military components.

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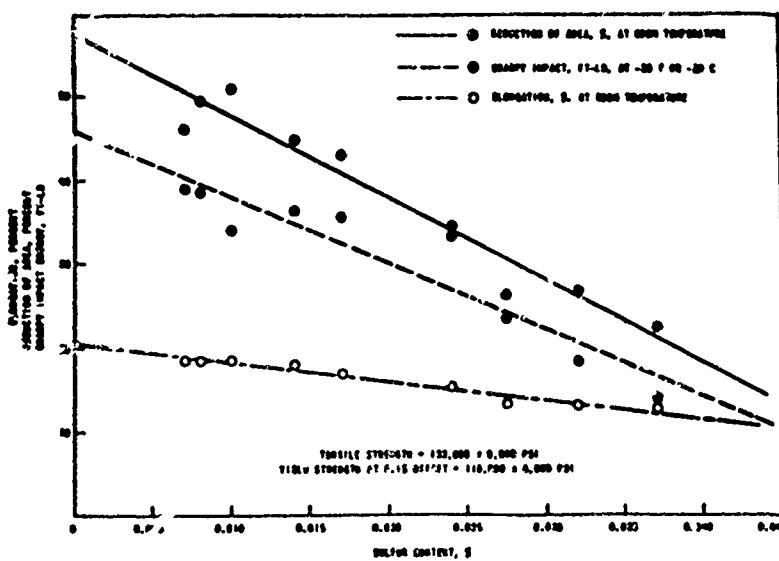
Fig. 1   Effect of Sulfur Content on Mechanical Properties of Cast High Nickel
4325 Steels (After Zotos)
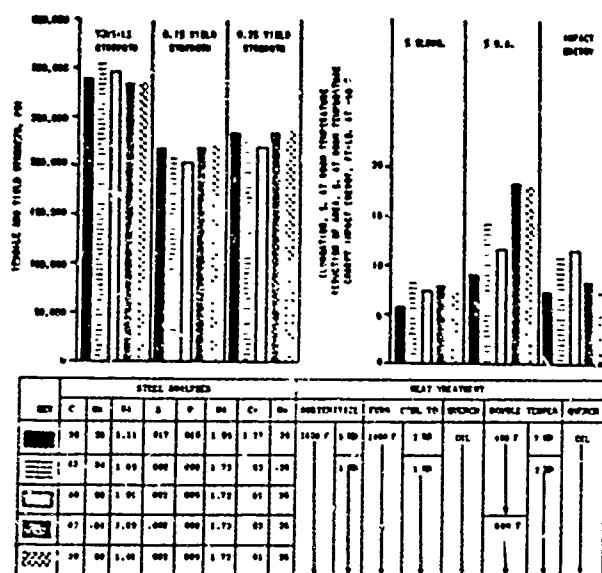
Fig. 2   Effect of Sulfur Content on the Ductility and Toughness of High Strength
Steel Castings (After Colling and Ahearn)

Fig. 3   Typical Macrostructure of Experimental Casting Cross Section
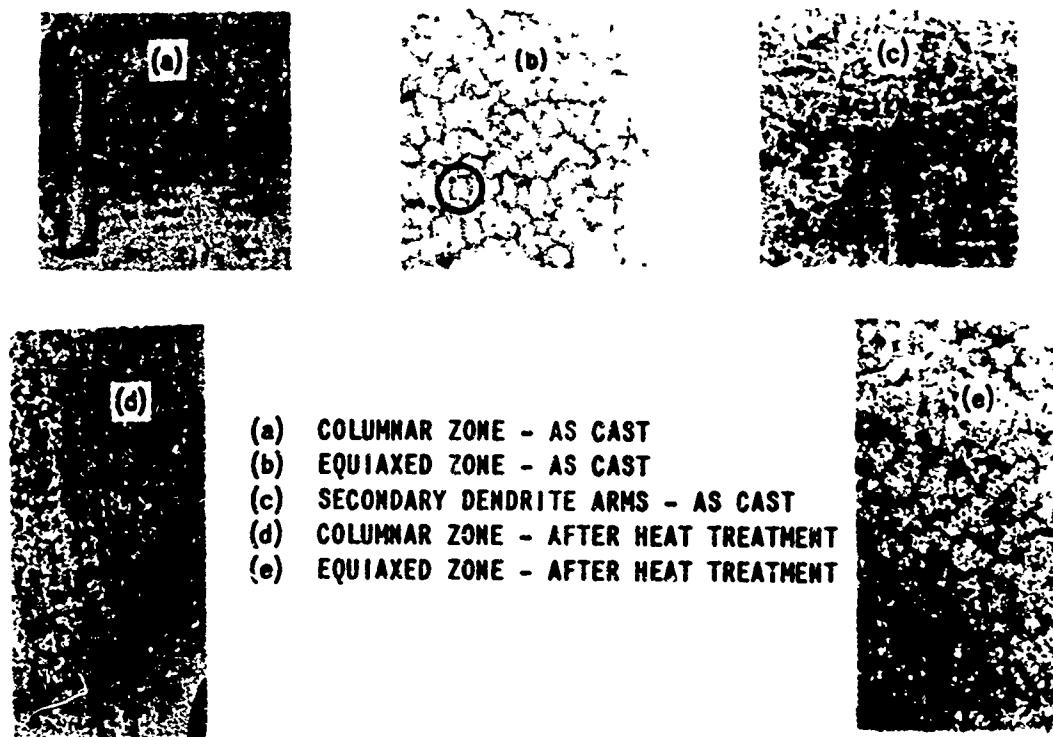
(a)   COLUMNAR ZONE - AS CAST
(b)   EQUIAXED ZONE - AS CAST
(c)   SECONDARY DENDRITE ARMS - AS CAST
(d)   COLUMNAR ZONE - AFTER HEAT TREATMENT
(e)   EQUIAXED ZONE - AFTER HEAT TREATMENT

Fig. 4   Metallographic Specimens Used for Microseggregation Studies.
Microanalysis is Limited to Enclosed Areas of Photomicrographs.
Magnification: 6X as Cast
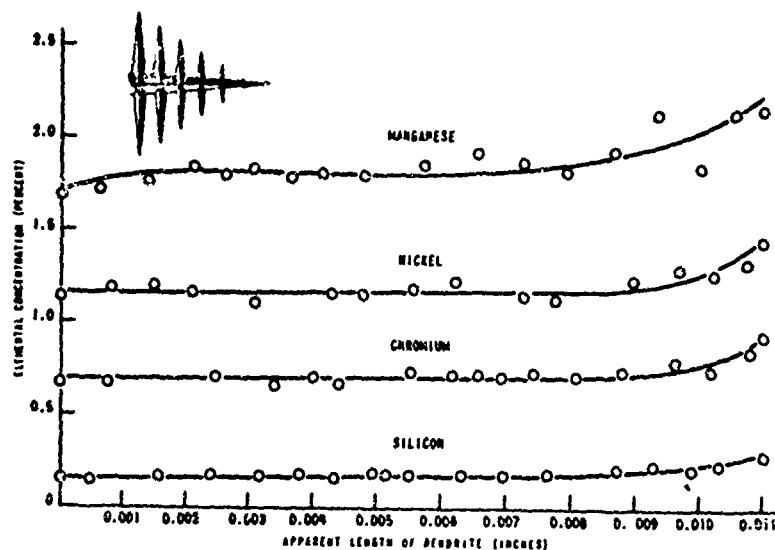
Fig. 5   Microsegregation Along a Dendritic Spine in the Columnar Zone - As Cast (After Colling Ahearn and Flemings)

Fig. 6   Microsecregation Across a Primary Arm of an Equiaxed Dendrite - As Cast (After Colling, Ahearn and Flemings)
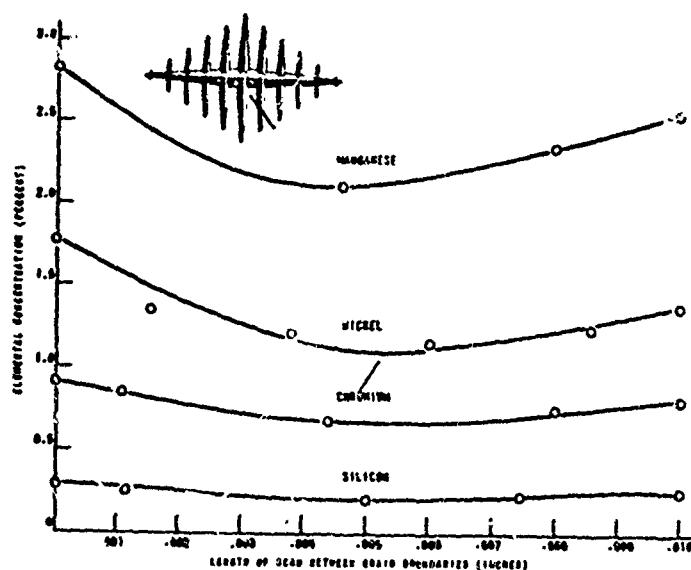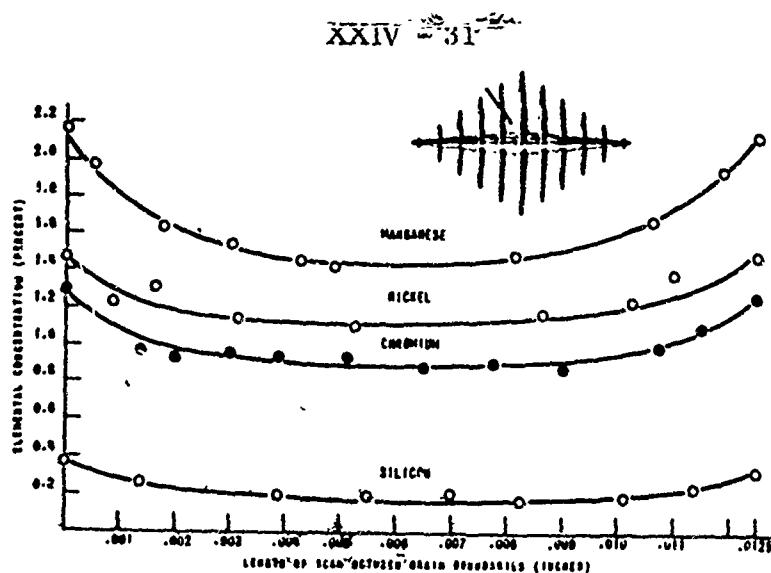
Fig. 7   Microsegregation Across a Primary Arm of an Equiaxed Dendrite -
After Heat Treatment (After Colling, Ahearn and Flemings)
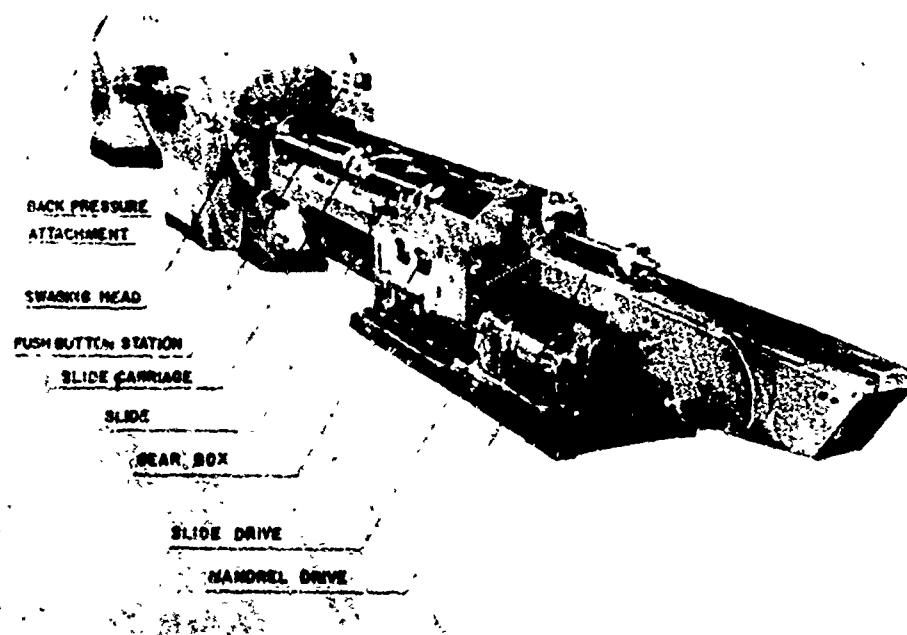
Fig. 8   Cold Swaging Machine - 200-Ton Capacity
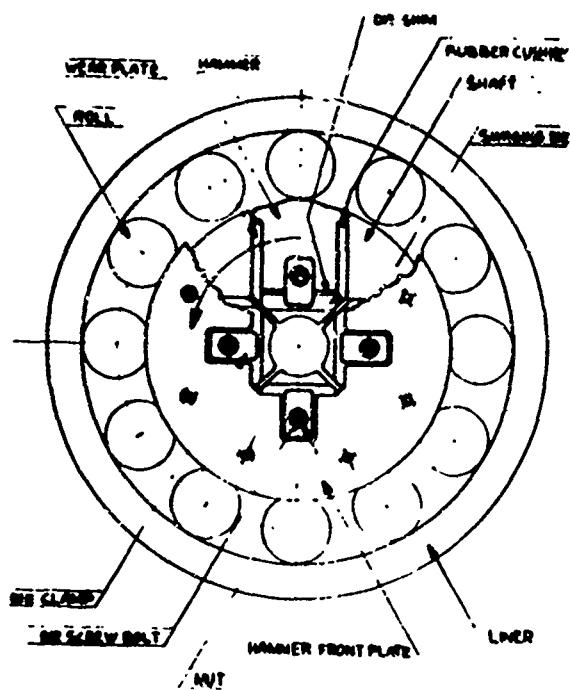
Fig. 9   **Head with Hammers in Closed Position**
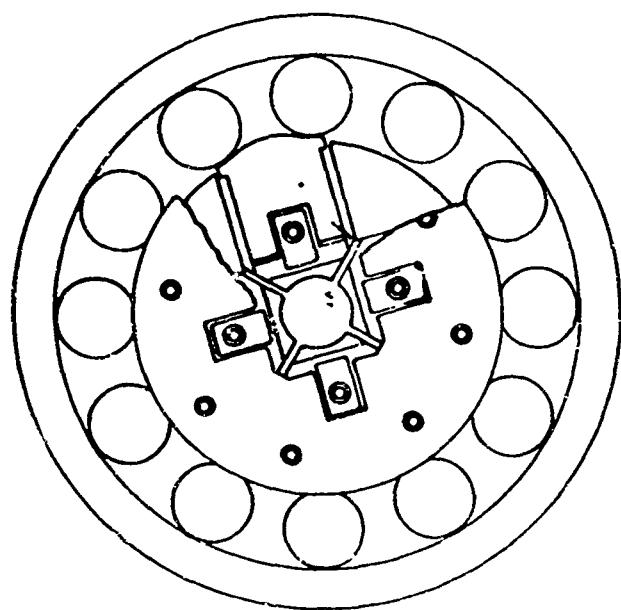
Fig. 10   **Head with Hammers in Open Position**

Fig.12   Rifle Barrel, .30 Caliber – Chamber and Rifling
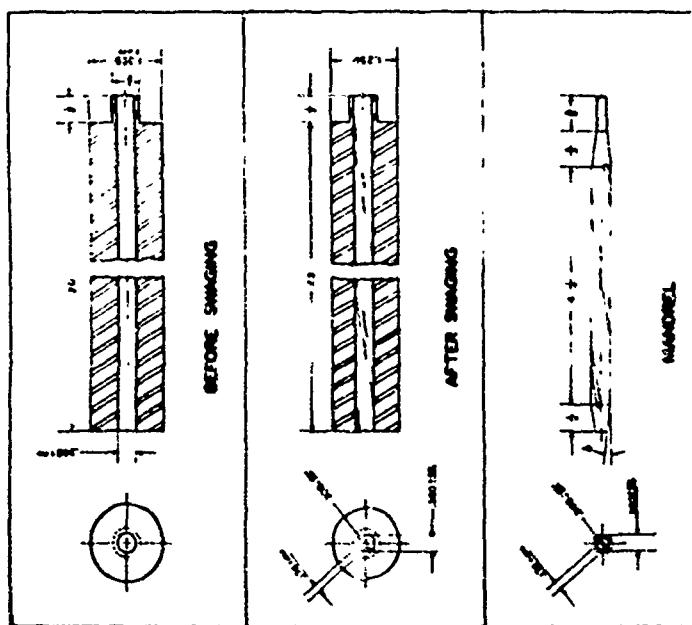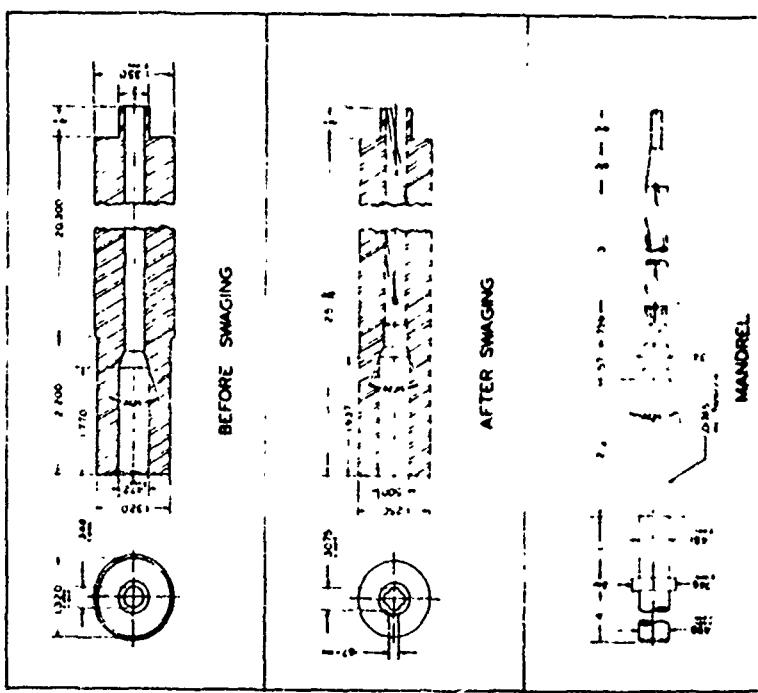
Fig.11   Rifle Barrel, .30 Caliber – Rifling

Fig. 15   Solid State Bonded Motor Casing —
Joint Location and Wall Thicknesses
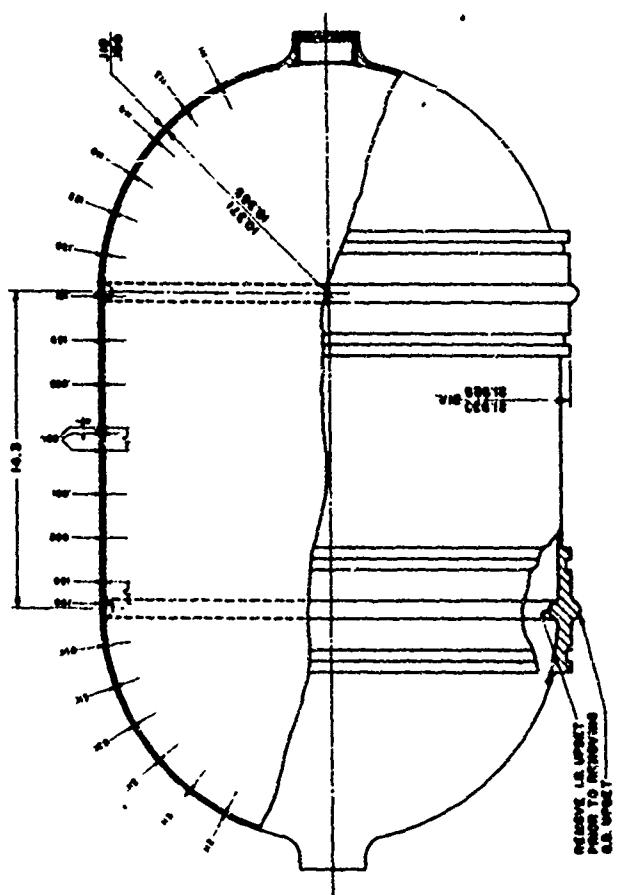
Fig. 13   Swaging Dies
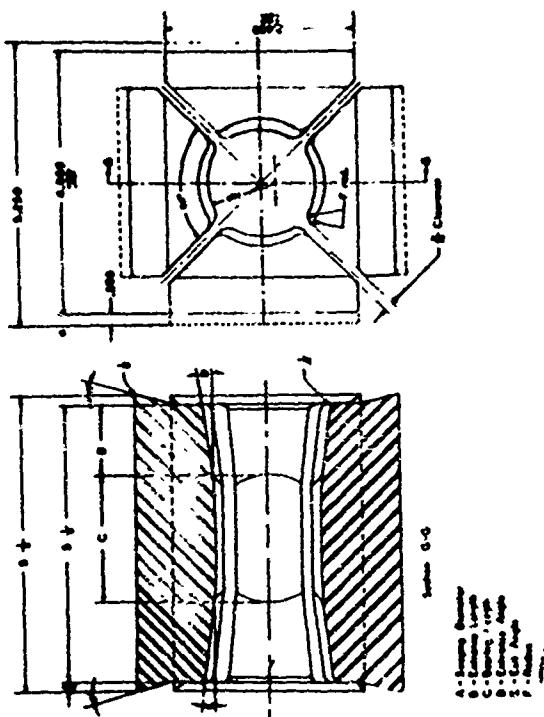
Fig. 14   Solid State Bonding Proof Testing
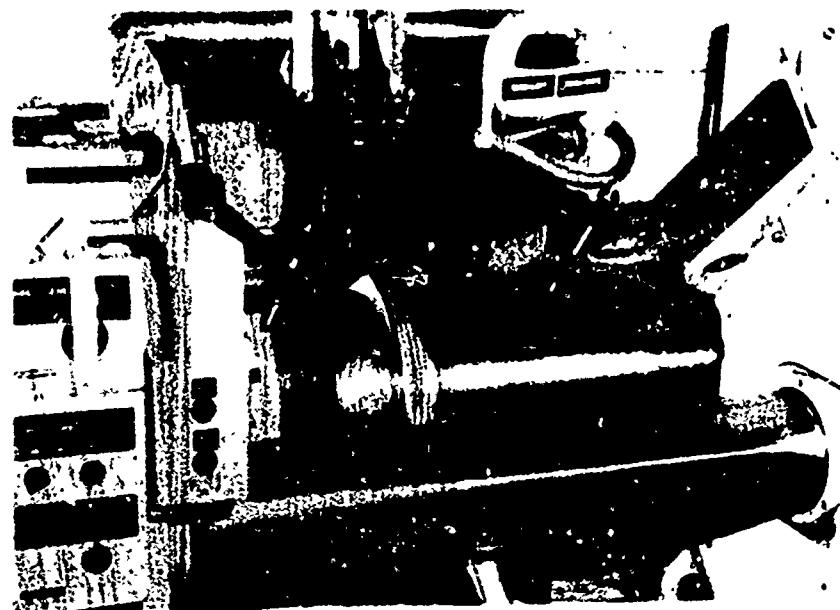
Fig. 16   Pressure Bonding Apparatus – During Bonding

(A) JOINT INTER-FACE
(B) SHOULDER
(C) APPLIED LOAD USING
    HYDRAULIC PISTONS
(D) ARGON
(F) OXYGEN, ACETYLENE
    FLAME RING
(F) UPSET
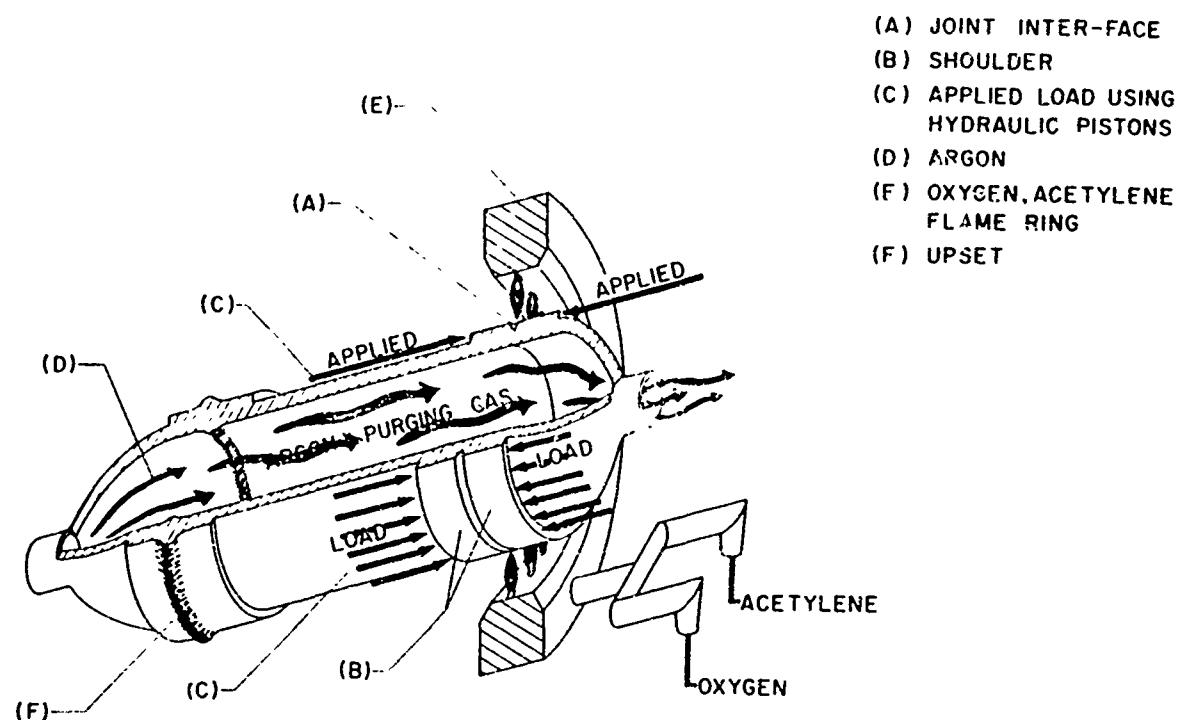
Fig. 17   Solid State Bonded Motor Casing – Bonding Procedure
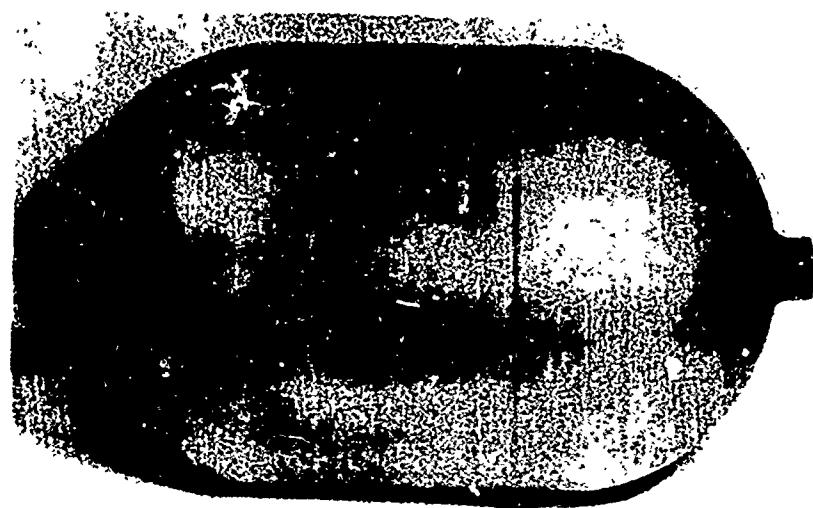
Fig. 18   Pressure - Bonded Casing - Machined

Fig. 19   High Energy Rate Forging Machine

PISTON AND RAM **LOW PRESSURE GAS**
HIGH PRESSURE GAS **HYDRAULIC FLUID**

COCKED   RELEASED   RE-COCKED
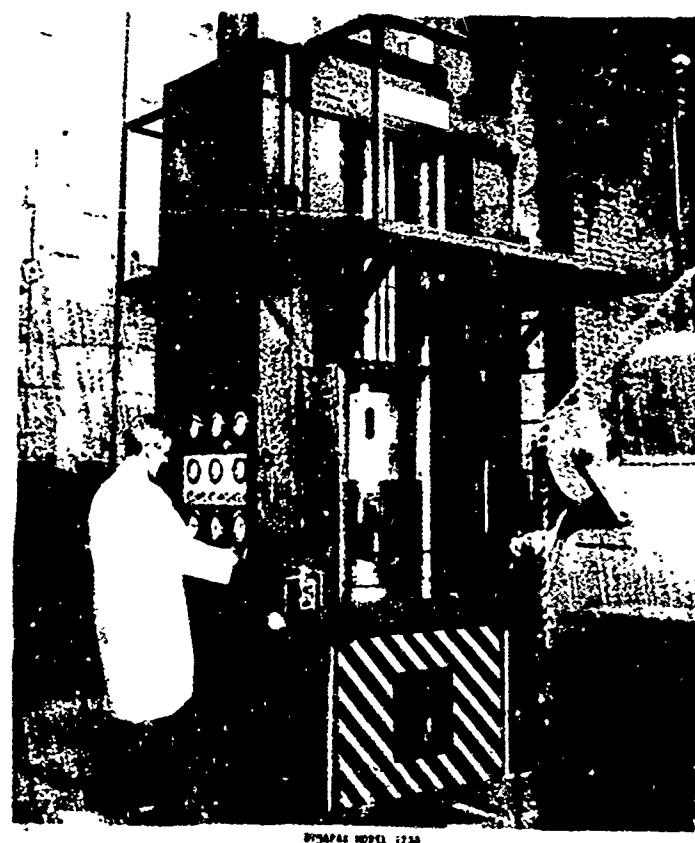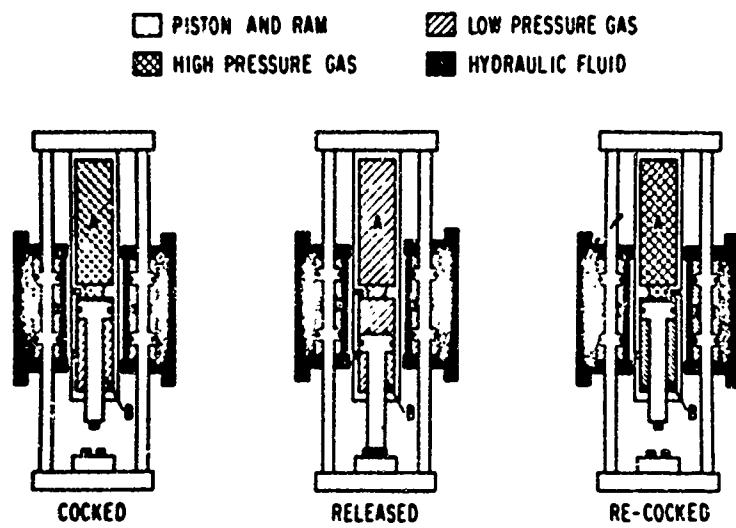
Fig. 20   High Energy Rate Forging Process

SECTION A-A
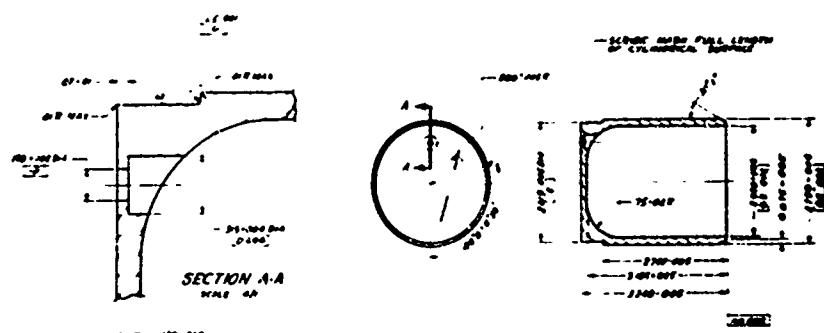
Fig. 21   Redeye High – Explosive Case
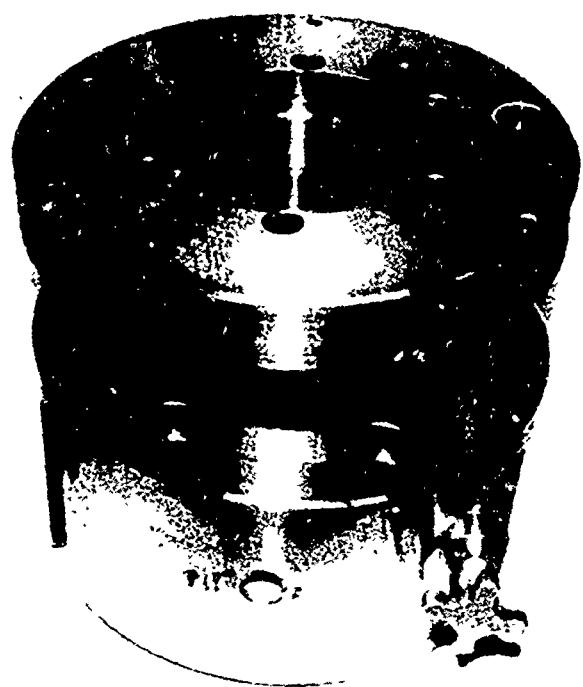
Fig. 22   Universal Die Holder and Striper

DIE (REDEYE COMPONENT)
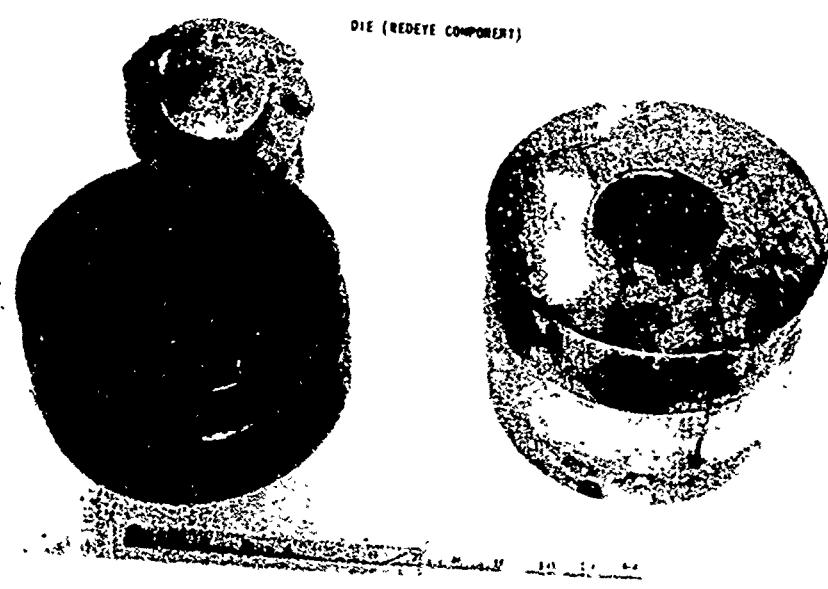
Fig. 23   Redeye Component
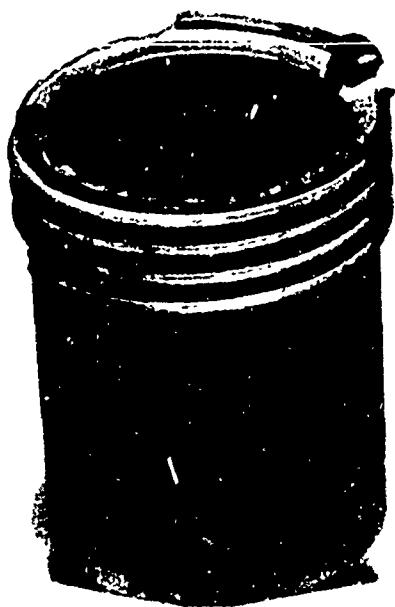
Fig. 24   Redeye Component Forged from GAP-4V-Ti Alloy
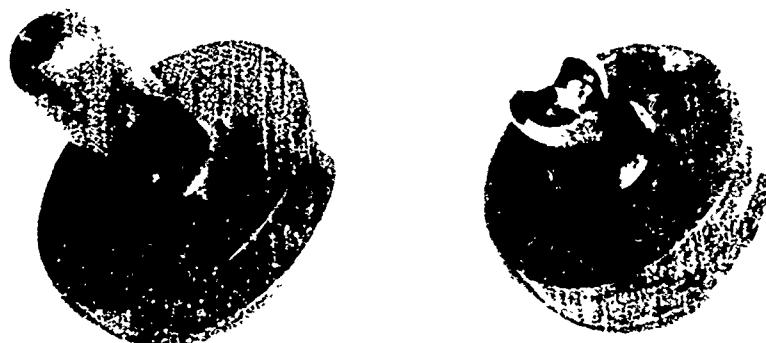
Fig. 25   Punch - Redeye Component

Fig. 26   Machine Tool

Fig. 27   Typical Tool - Holder for Throw-Away Carbide or Ceramic
Blanks
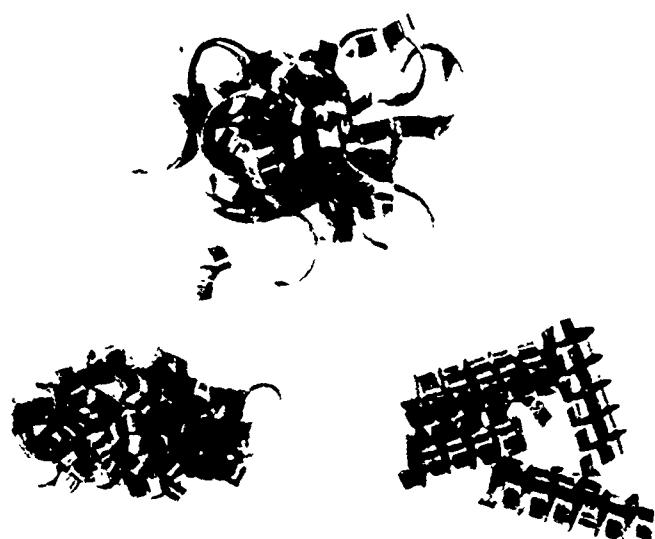
Fig. 28   Chips Produced with Ceramic Cutting Tools

A PRODUÇAO DE ELETRODOS GIRANTES PARA SOLDAGEM EM LIGA COBRE-COBALTO-SILÍCIO(*)

Sérgio Augusto de Souza (**)
Luiz C. Correa da Silva (***)

RESUMO - O trabalho relata a experiencia da Divisao de Metalurgia do Instituto de Pesquisas Tecnológicas de Sao Paulo na produçao de eletrodos girantes em liga cobre-cobalto-silício, para utilizaçao em máquinas de soldar. Os trabalhos realizados no I. P. T. visaram atender, no possivel, as necessidades da indústria local e evitar a total dependencia de importaçoes. Apresenta-se um resumo dos principais fatos e dados referentes aos eletrodos para máquinas de soldar. Descreve-se: a técnica de fundiçao dos aneis; o método de dimensionamento dos mesmos para conveniente forjamento posterior; a técnica de forjamento empregada e a execuçao dos tratamentos térmicos necessários. Sao apresentadas macro e micrografias visando ilustrar a estrutura dos eletrodos fundidos e forjados e dos eletrodos fundidos, forjados e tratados termicamente.

1. INTRODUÇAO

A Secçao de Ligas Nao-Ferrosas do Instituto de Pesquisas Tecnológicas tem recebido, frequentemente, pedidos para confecçao de aneis em liga de cobre de alta condutividade para serem usados como eletrodos girantes. Os pedidos va riam quanto ao tamanho dos mesmos e quanto a liga, que pode ser de cobre-cro mo, cobre-níquel-silício, cobre-cromo-silício ou cobre-cobalto-silício. Atual mente a primeira e a última das ligas mencionadas estao sendo preferidas, prin cipalmente a liga cobre-cobalto-silício, que é objeto deste trabalho.

A princípio, para atender os interessados, o processo usado era o de se fundir simplesmente as peças e entregá-las no estado bruto de fusao, para que aquéles fizessem os tratamentos térmicos necessários. Algumas peças apresen tavam defeitos de fundiçao, tais como: bolhas, porosidades, inclusoes de escó ria, trincas, sendo entao decidido mudar-se o processo de confecçao dos aneis, passando-se a forjá-los, depois de fundidos convenientemente. Devido ao caráter especial deste processo, relata-se aquí o estudo relativo as condiçoes de fundi çao e de forjamento desses aneis.

2. CARACTERÍSTICAS DESEJÁVEIS PARA OS ELETRODOS

Um eletrodo girante para solda elétrica contínua de tubos, aplicaçao prin cipal destes aneis, deve apresentar as seguintes propriedades[1][2]:

a. Dureza elevada, entre 120 e 200 Brinell.

b. Dureza elevada mesmo a altas temperaturas.

c. Condutibilidade elétrica e térmica elevadas.

d. Boa resistencia mecánica.

e. Reduzida tendencia de se fundir com as peças a serem soldadas. A isto, deve-se o grande desgaste a que o anel fica sujeito durante o seu uso.

3.   TÉCNICA UTILIZADA NAS EXPERIENCIAS REALIZADAS

A técnica utilizada consistiu nas seguintes operaçoes: fundiçao dos aneis em areia, seguindo-se a rebarbaçao e forjamento desses aneis fundidos até as di mensoes desejadas, de tal modo a garantir cerca de 50% de reduçao na espessura; por fim, seguiram-se os tratamentos térmicos necessários.

No forjamento há naturalmente, uma variaçao dimensional de difícil previ sao, sendo necessário estudá-la no decorrer da operaçao. Para facilitar o estudo fundiu-se um anel menor que os que se tem feito habitualmente, mas cujas di-mensoes guardaram as mesmas proporçoes dimensionais que estes.

O processo de forjamento foi realizado medindo-se a espessura, o diame-tro interno e o diametro externo do anel em diversos estagios da operaçao. Para os objetivos deste estudo considerou-se que uma deformaçao de 50% era satisfató ria (diminuiçao da espessura do anel a metade da inicial). Esta deformaçao deve normalmente ser suficiente para assegurar o fechamento de bolhas e porosidades internas, bem como para promover uma estrutura mais fina em consequencia de recristalizaçao.

4.   EXPERIENCIAS REALIZADAS

Com a finalidade de melhor esclarecer o trabalho realizado, parece inte-ressante apresentar um relato mais detalhado das duas primeiras experiencias realizadas. É de notar, porém, que após essas experiencias que visaram a ob-tençao de dados sobre o comportamento dos aneis no forjamento, foram produzi dos com sucesso mais de dez aneis forjados, para atender a solicitaçoes da in-dústria local. Os resultados de mais dois forjamentos sao dados em tabela no fim do trabalho.

4.1.   Primeira experiencia

Fundiçao

O processo usado para a fundiçao do anela ser forjado nao se di-ferenciou muito do utilizado habitualmente.

As dimensoes do modelo usado para a confecçao do anel foram as

seguintes:

Diametro externo (D): 53 cm
Diametro interno (d): 37 cm
Espessura: 10 cm

O molde foi feito com a seguinte areia:

Areia do mar:	60% (módulo de finura: 90 a 100 AFS)
Areia usada:	40% (módulo de finura: 90 a 100 AFS)
Argila:	4% da areia base
Mogul:	1,5% da areia base
Óleo + breu	2% da areia base
Água:	5% da areia base

O molde foi estufado a cerca de 200º C durante duas horas, sendo depois colocado inclinado de mais ou menos 10º, com relaçaoa horizontal, para o vazamento (Figs. 1 e 2).

O sistema de alimentaçao esta indicado nas Figuras 1 e 2. Foi feito um canal de descida oposto ao massalote; partindo desde canal há 2 canais de distribuiçao cada um com 3 canais de ataque (de entrada). O massalote único ficou situado na parte mais alta do molde. Assim, conseguiu-se que o metal, ao entrar, percorresse todo o molde, nos dois sentidos e tangencialmente as paredes do mesmo, indo se encontrar praticamente no massalote. A inclinaçao dada serviu para ajudar a alimentaçao. As dimensoes dos canais foram as seguintes:

Canal de descida:	diametro de 4,5 cm
Canal de distribuiçao e canais de ataque:	largura de 6 cm e espessura de 2 cm
Massalote:	largura de 10 cm, espessura de 30 cm, e comprimento de 15 cm
Junçao do massalote a peça:	largura de 6 cm; espessura de 11,5 cm, e comprimento de 6 cm.

O molde foi pintado com mistura de grafita, dextrina, bentonita e água.

Fusao da liga: a liga fundida deveria ter a seguinte composiçao: 2,5% Co, 0,5% Si e o restante cobre. Como as perdas por oxidaçao do cobalto e do silício sao relativamente elevadas, adicionou-se um excesso de 0,5% Co e de 0,3% Si para compensá-las.

A preparaçao da liga procede-se habitualmente como segue: prepa ra-se primeiramente uma liga auxiliar ("liga-mae") de cobre com todo o cobalto e silício; funde-se o cobre, protegido da atmosfera por escória apropriada, para evitar excessiva oxidaçao do banho, embora este deva estar levemente oxidado a fim de se eliminar ou evitar a entrada de hidrogenio. Quando o cobre estiver fun dido, adiciona-se a liga auxiliar, retira-se a escória e procede-se ao vazamento. A desoxidaçao da liga é feita pelo próprio silício de carga, o qual é colocado em excesso.

Na primeira experiencia realizada aproveitou-se, porém, sucata de aneis defeituosos e de canais de corridas anteriores, usando-se somente 50% de carga nova. Cobriu-se o banho com uma mistura de borax e vidro em cacos, para proteçao. Depois de fundida a carga e colocada a "liga-mae", retirou-se a escória fluida e procedeu-se ao vazamento a 1200º C aproximadamente. Do forno (que no caso era um forno tipo Fisher, a óleo com cadinho carborundum), vazou-se numa panela préaquecida dotada de "bico de chaleira" para depois vazar-se no molde. A liga auxiliar foi preparada num forno de induçao, tipo Ajax, em cadinho de grafita.

Retiraram-se cavacos dos canais para análise química, a qual acu sou 2,81% Co e 0,68%Si. Assim, verificou-se que basta um excesso de 0,2 a 0,3% Co e de 0,2% Si para que a liga final fique dentro da especificaçao.

A dureza da peça simplesmente fundida foi de 47 Rockwell B.

As dimensoes da peça fundida foram as seguintes:

Diametro externo (D): 53 cm
Diametro interno (d): 36 cm
Espessura: 9,9 cm

Defeitos e dificuldades observados:

a)   Aparecimento de "chupagem" na parte onde o massalote esteve uni do a peça. Esta dificuldade foi vencida pelo uso de um massalote dotado de uma junçao mais grossa e melhor dimensionado, conforme arti-gos especializados em cálculo de canais em ligas de cobre[3][4].

b)   Aparecimento de uma superfície rugosa e acidentada na parte onde o metal entrou na peça pelos canais de ataque. Conseguiu-se melho rar muito o aspecto da superfície, colocando-se os canais de ataque tangen ciais a peça.

c)   A entrada de escória no molde foi evitada com o uso do "bico de

leira" na panela de vazamento.

Forjamento

Depois de rebarbada a peça, ela foi encaminhada para o forjamento. Nesta primeira peça, procurou-se apenas verificar a sua forjabilidade e o modo como se deformava durante a operaçao.

Aqueceu-se o anel até cerca de 900º C e forjou-se até uma espessura de 6 cm, medindo-se, entao, os diametros interno e externo, de modo a se ter uma primeira idéia das deformaçoes. A seguir, voltou o anel para o forno de aquecimento (forno aquecido a óleo com maçarico), a fim de reaquece-lo a 900º C. Forjou-se depois até uma espessura total de 5 cm e procedeu-se a medida dos diametros. Teve-se uma reduçao de 50% de forjamento. A tabela seguinte fornece os resultados.

Espessura (cm)	D (cm)	d (cm)
9,9 (inicial)	53	36
6,0	64	43
5,0	66	44,5

A peça forjou bem, nao apresentando empenamento, deixando apenas de permanecer perfeitamente redonda (as medidas dos diametros externo e interno corresponderam a médias de várias medidas, pois em certas regioes da peça houve maior ou menor alargamento). Isso deveu-se a forjamento nao uniforme, forjando-se mais fortemente algumas partes e menos outras. Na regiao onde estava situado o massalote notou-se o início de uma trinca superficial, demonstrando ser essa uma regiao crítica.

Constatou-se, portanto, que a liga usada é perfeitamente forjável na temperatura inicial de 900º C e que, para se obter alargamento uniforme, nao se deve usar o martelo de forja muito fortemente ou com pancadas desiguais.

A dureza da peça forjada subiu para 52 Rockwell B.

Tratamento térmico

Sendo esta questao muito crítica para o caso de ligas de cobre de alta condutividade, pois é o que determina praticamente as propriedades mais importantes para o uso da liga, será feito um estudo que tratará exclusivamente deste problema, e que será objeto de trabalho posterior. No entanto, convém citar os resultados obtidos.

Depois de forjada, a peça foi submetida a um tratamento de solubilizaçao e precipitaçao. Estes tratamentos foram feitos da seguinte maneira:

- Solubilizaçao: aqueceu-se a peça a 900º C durante 2 horas, resfriando-se em água.

- Precipitaçao: aqueceu-se a peça a 450º C durante 3,5 horas, resfriando-se ao ar.

A dureza obtida após a solubilizaçao foi de 54 Rockwell B. A dureza obtida após a precipitaçao foi de 76 Rockwell B.

4.2. Segunda experiencia

Fundiçao

A técnica de fundiçao usada foi a mesma já descrita, exceto no que diz respeito a matéria prima: devido ao excesso de cobalto e de silício verificado na análise da corrida anterior, adicionou-se menor quantidade desses elementos. Assim, os teores de cobalto e de silício introduzidos na carga por intermédio da liga auxiliar foram de 2,8% Co e 0,7% Si, o que correspondeu a um excesso de apenas 0,3% Co e 0,2% Si.

A análise química desta segunda corrida revelou: 2,76% Co e 0,52% Si, o restante sendo cobre, composiçao essa geralmente recomendada para esta liga.

Procedeu-se normalmente ao vazamento, inicialmente pelo canal de descida até encher a peça, terminando por vazar pelo massalote para melhor assegurar a limentaçao.

As medidas da peça fundida foram as seguintes:

Diametro externo (D): 53 cm
Diametro interno (d): 35,5cm
Espessura: 9,8cm

As dimensoes dos canais foram as seguintes:

Canal de descida:	diametro de 5 cm
Canal de distribuicao:	largura de 6 cm e espessura de 2 cm
Tres canais de ataque:	largura de 6 cm cada um e espessura de 2 cm
Massalote:	largura de 10 cm, espessura de 28 cm e comprimento de 20 cm
Juncao do massalote a peça:	largura de 8 cm, espessura de 13 cm e comprimento de 8 cm

Forjamento

O forjamento da peça foi realizado conforme foi programado, isto e, partindo de uma espessura de 10 cm (praticamente), forjou-se em etapas, reduzindo-se a espessura de centímetro em centímetro até atingir-se uma espessura final de 5 cm aproximadamente. Cada vez que era reduzida a espessura de 1 cm, media-se o diametro externo e o diametro interno para se observar a deformaçao. Após cada medida, a peça retornava ao forno de aquecimento para atingir-se de novo a temperatura de forjamento (900º C). Obteve-se, assim, a seguinte tabela:

Espessura (cm)	D (cm)	d (cm)
9,8	53	35,5
9,0	56	38
8,0	57	40
6,8	61,5	41,5
5,9	65,5	43
5,0	67	44

Tratamento térmico

Foi o mesmo que na experiencia anterior.

5. ANÁLISE DOS RESULTADOS OBTIDOS

Com as medidas feitas, pode-se traçar alguns gráficos úteis para predizer a deformaçao dos aneis durante o forjamento (Figs. 3 e 4).

Para generalizar os resultados obtidos, é interessante exprimí-los também, em porcentagens de aumento de D e d, em funçao da espessura h (Figs. 5 e 6). Estes últimos gráficos dao as medidas em que deverao ser forjados os aneis de qualquer tamanho, em liga cobre-cobalto-silício, para se obter, no final, as dimensoes desejadas para os mesmos.

Cálculo das porcentagens de aumento nos diametros D e d: Chamando de Δ D e de Δ d as porcentagens de aumento nos diametros externo e interno, respectivamente, e de Δ h as porcentagens de reduçao da espessura, tem-se:

$$\Delta D \text{ ou } \Delta d = \frac{\text{dimensao após algum forjamento - dimensao inicial}}{\text{dimensao inicial}} \times 100$$

Obteve-se, assim, a tabela das porcentagens de reduçao na espessura e do aumento nos diametros. Dos dados desta tabela, conclui-se que durante a reduçao da espessura dos aneis a metade, por forjamento, nos diametros externo e interno aumentam de cerca de 25%. Naturalmente que, para cada caso, é necessário fazer-se uma experiencia prévia para se determinar exatamente a variaçao das dimensoes.

6. ESTRUTURA DAS PEÇAS

Foram realizados alguns exames metalográficos com o objetivo de melhor aquilatar o efeito do forjamento e do tratamento térmico.

As macro e micrografias das Figuras 7, 8, 9 e 10 ilustram os tipos de estrutura observados. É facilmente observável a melhoria da estrutura pelo forja-

Tabela das porcentagens de reduçao na espessura
e do aumento nos diametros

$\triangle h$ (%)	$\triangle D$ (%)	$\triangle d$ (%)
1a. Experiencia		
40	20,7	19,5
50	24,5	23,6
2a. Experiencia		
10	5,7	7
20	7,5	13
30	16	17
40	23,5	21
50	26,5	25
3a. Experiencia		
10	7,5	5
20	12	9
30	17	12,5
40	24	21
50	26	24
4a. Experiencia		
10	7,5	9
20	12,5	13,5
30	16,5	18
40	22	23
50	25	25

mento seguido do tratamento térmico.

7.   CONCLUSOES

Da experiencia adquirida na Secçao de Ligas Nao-Ferrosas da Divisao de Metalurgia do I.P.T., pode-se concluir o seguinte:

a.   A produçao de eletrodos girantes para solda de tubos é problema que vem preocupando a indústria nacional, obrigada a importa-los ou a lançar mao de uma produçao local ainda insuficiente em quantidade e qualidade.

b.   A produçao de aneis de boa qualidade para eletrodos girantes, apenas por fundiçao, é difícil. O forjamento, garantindo a compacidade das peças bem como promovendo um refino de grao (por recristalizaçao), permite a obten ção de peças de boa qualidade e adequadas para a aplicaçao em vista.

c.   O forjamento provoca uma alteraçao das dimensoes, que precisa ser estu dada previamente. No caso dos aneis estudados no I.P.T. observou-se que, para uma reduçao da e_pessura de 50%, os diametros interno e externo au- mentavam de cerca de 25%.

d.   Para melhor estudar e resolver os problemas de produçao de eletrodos girantes, nao só de Cu-Co-Si como de outras ligas de cobre de alta condu tividade, de modo a divulgar a técnica e melhor atender as necessidades da nossa indústria, é necessário prosseguir nos trabalhos iniciados, o que será feito pelo I.P.T.

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PROPIEDADES DE UNA ALEACION DE COBRE DE ALTA RESISTENCIA AL ABLANDAMIENTO Y ALTA CONDUCTIVIDAD

por D. Obrutsky, M. Sarrate y O. Wortmann

Introducción

Trabajos previos de Saarivirta (1) y Saarivirta y Taulenblat (2) muestran que las aleaciones binarias Cu-Zr ofrecen interesantes perspectivas en el campo de las aleaciones de alta conductividad y alta resistencia mecánica a moderadas temperaturas.

En efecto, estas aleaciones aparentan tener ventajas sobre las aleaciones actualmente en uso, principalmente Cu-Cr y Cu-Ag. Su elevada conductividad en el estado de solubilizadas y envejecidas, así como sus propiedades de resistencia al creep y resistencia a la rotura a temperaturas del orden de 400ºC, las convierten en materiales interesantes para ser utilizados en la industria eléctrica de conductores, conmutadores, transformadores, contactos, etc.

Una aplicación importante es la de electrodos para máquina de soldar por resistencia. Cu-Zr por su resistencia al creep ofrece la posibilidad de obtener electrodos de gran durabilidad.

El SATI decidió encarar el estudio de la cinética de precipitación de estas aleaciones dado que la bibliografía no ofrece mucha información que es necesaria para la aplicación industrial de las mismas.

PROCEDIMIENTO EXPERIMENTAL

Se fundieron aleaciones de Cu-Zr de las composiciones que se muestran en la Tabla I. Se partió de Cu cátodo y Zr (pureza 98%). Las aleaciones se fundieron en horno de inducción, bajo una atmósfera de 400 mm Hg. de A.

Los lingotes obtenidos tienen las siguientes dimensiones:
$\emptyset$ = 40 mm   L = 200 mm

Estos lingotes se extrudaron e alambrón de 20 mm $\emptyset$ con una relación de extrusión de 4 : 1 y una temperatura de 850°C.

Los distintos ensayos físicos se realizaron sobre alambre trefilado.

Dureza fué medida sobre un alambre de	$\emptyset = 5$ mm	Long. aprox.	5 mm
Corte, en microprobetas de	$\emptyset = 1,5$ mm	Long. aprox.	25 mm
Resistividad, en alambre de	$\emptyset = 0,5$ mm	Long. aprox.	400 mm
Fuerza electromotriz termoeléctrica en			
alambre de	$\emptyset = 0,5$ mm	Long. aprox.	400 mm

El trefilado del alambrón de 20 mm se realizó en pasadas de 10%, con recocidos intermedios bajo atmósfera de A recubriendo las barras, en todos los casos, con una pintura protectora.

TABLA I

Probeta	Contenido de Zr en %
1	0.26
3	0.20
5	0.16
6	0.13
7	0.11
8	0.10
9	0.08
10	0.05
17	0.03

El límite de solubilidad de Zr en Cu es motivo de discusión. Saarivirta (1), en base a determinaciones metalográficas, ha establecido que es de 0.15% en peso a 980°C. Para Showak (3) por otra parte, es de 0.24 a esa temperatura, mientras que Donachie (4), utilizando la microsonda de Castaing, da el valor 0.17%, que se acerca al de Saarivirta.

En este trabajo hemos adoptado como límite de solubilidad de Zr en Cu el valor de 0.15% en peso a 980°C.

ESTUDIO DE PRECIPITACION

Se han utilizado distintas propiedades (5) a fin de seguir la precipitación de Zr.

Dureza VPH
Metalografía
Conductividad
Fuerza electromotriz termoeléctrica
Rayos X
Dilatometría
Ensayos de corte

Estos ensayos se realizaron sobre probetas que han tenido 0% y 75% de de formación previa en frío. La temperatura de solubilización es en todos los casos de 950°C.

Dureza

En las figuras 2, 3 y 4 se observa la variación de dureza en función del tiempo para probetas de diferentes tenores de Zirconio envejecidas a 500oC, 400oC y 300°C con 75% de deformación inicial.

En las curvas de 400oC y 500°C se observa en ambos casos la presencia de un pico de dureza que está entre los $2\frac{1}{2}$ y 5 minutos. Lo anterior vale para composiciones comprendidas entre 0.08 y 0.26%.

A 300oC y 200oC la cinética es mucho más lenta, estableciéndose los picos de dureza en 2 horas a 300oC y entre 72 y 96 horas para 200oC.

Se observa que adiciones de 0.08% de Zr elevan sensiblemente la tempera tura de recristalización. A 300oC la probeta con 0.08% Zr mantiene su dureza luego de 250 horas.

Para las probetas con tenores de 0.13% de Zr o superiores, los Δ H máxi mos se obtienen para un tratamiento de envejecimiento de 5 min. a 500oC.

En la figura 5 se han resumido los datos anteriores para la probeta 5 (0.16% Zr);construyéndose la familia de isócronas.

Del análisis de éstas se verifica que a diferencia de lo que ocurre en Al-Ag, en la cual aparecen dos picos en la curva, en este caso un solo mecanismo aparenta ser responsable del endurecimiento.

Probetas solubilizadas con 0% de deformación inicial

Para temperaturas de 400oC y 500°C se ha observado que los máximos va lores de dureza se obtienen para 80 horas y 15 min. respectivamente. En las me talografías de las figuras 6 y 7 tomadas con tratamientos térmicos de 60 min. a 500oC se observa la presencia de una estructura de Widmanstätten característica.

la fase precipitada es de composición Cu_3Zr (1) (2) (6). Dada la similari
dad en dimensiones cristalográficas entre Ti y Zr es razonable suponer que aná
logamente a lo que ocurre en aleaciones Cu Ti (7) la que precipita es una fase or
denada Cu_3Zr, isomorfa con el Cu_3Ti (8) (9).

Dilatometría y Rayos X

En este trabajo se han hecho determinaciones dilatométricas utilizando un
dilatómetro Chevenard, realizando envejecimientos isotérmicos en el rango 200ºC
a 500ºC. Con la precisión con que se contaba, en ningún caso se pudo observar va
riación de longitud. El coeficiente de amplificación del dilatómetro es = 1100.

Las mediciones de parámetro de red se realizaron con precisión de 1×10^{-3} Å
utilizando el método de polvos con Cámara Debye Scherrer.

El parámetro se midió utilizando los dobletes $K\alpha_1$ $K\alpha_2$ para los planos 331
y 420.

Se estudiaron probetas de composiciones crecientes de Zr 0.08, 0.13, 0.20
y 0.26 solubilizadas a 950ºC y templadas.

No se observa que para composiciones crecientes el parámetro de red varíe
con la composición.

Para probetas envejecidas no se observa la presencia de una segunda fase.
Esto es explicable dada la pequeña cantidad de Zr presente.

Ensayos mecánicos

Con el objeto de comparar cualitativamente los distintos tratamientos tér-
micos para diferentes composiciones se realizaron ensayos de corte usando la mi
cromáquina Chevenard. En dicho equipo la curva τ en función de la deformación
se inscribe por medio de registro fotográfico.

En la figura 8 se han representado los valores de $\tau_{0.8}$ que provocan una
deformación permanente igual a 0.8% del diámetro inicial. Esto se ha tomado co
mo índice cualitativo de la resistencia a la deformación plástica del material.

Las propiedades mecánicas (flow stress) aumentan con el contenido de Zr
hasta alcanzar un máximo para valores de Zr de aproximadamente 0.17% en peso.

Del análisis de la figura se observa que existe una caída en el valor de $\tau_{0.8}$
al progresar el proceso de envejecimiento, caída que aumenta cuanto menor es el
contenido de Zr.

Este efecto se manifiesta aún más claramente en la figura 9 en la que se ha representado el valor de $\tau_{0.8}$ en función del tiempo de envejecimiento a distintas temperaturas para un contenido de 0.16% de Zr, con deformación previa del 75%.

Esta disminución inicial no concuerda con las curvas de dureza a esta misma temperatura (figura 2).

Dicha anomalía se atribuye a que el ensayo de corte se realizó en un plano normal al eje de trefilado.

La textura que es dable esperar en alambre trefilados de cobre consiste en forma preponderante de cristales con la dirección [100] y [111] paralela a la dirección de trefilado. La precipitación de Cu$_3$Zr, que se realiza en planos preferenciales, produce fuerte direccionalidad en las propiedades mecánicas.

Conductividad

Medir la conductividad es una técnica importante para seguir cinéticas de precipitación.

En efecto (10) variaciones grandes de conductividad deben atribuirse preponderantemente a "clustering" o precipitación de átomos de soluto.

La medición de conductividad se realizó utilizando un potenciómetro K3 Leeds y Northrup.

Se mide la tensión sobre la probeta incógnita y sobre una resistencia patrón invirtiendo la corriente para evitar influencias de las resistencias de contacto. Luego de realizadas dos medidas con la corriente en distintos sentidos se promedian los resultados.

En la figura 10 se ha representado las curvas isócronas para 1 h. y 24 hs. de envejecimiento de Cu – 0.16% Zr con 0% y 75% de deformación. Se observa un aumento continuo de la conductividad con la temperatura del tratamiento térmico.

Los valores absolutos muestran que las probetas deformadas 75% alcanzan para iguales tiempos mayores valores de conductividad.

Esto es razonable teniendo en cuenta que la presencia de defectos producidos por el trabajado aumenta la cinética de precipitación.

Es decir, son necesarios menores tiempos para alcanzar iguales niveles de precipitación en probetas que han sufrido deformación en frío.

Fuerza electromotriz termoeléctrica

Se midió la fuerza electro motriz producida al calentar a 100ºC una termo-
cupla construída de la siguiente manera:

a)   Un alambre de C·t recocido.

b)   Un alambre de Cu-Zr solubilizado templado y envejecido por pe-
ríodos diferentes.

En todos los casos se refirió la tensión al valor que se obtendría tomando
como uno de los elementos del par un alambre de Cu-Zr solubilizado y templado.

En la figura 11 se observa la variación de la fuerza electromotriz termo-
eléctrica para probetas con 0.16% de Zr.

Tal como se puede apreciar, la f. e. m. cambia en forma parecida a la
conductividad en función del tiempo de envejecimiento (Fig. 11).

Energía de activación del proceso de precipitación

Si se supone que la precipitación es un proceso controlado por difusión, la
expresión de velocidad de transformación responde a una expresión de la forma

$$\frac{1}{t} = e^{-\frac{Q}{RT}}$$

siendo t el tiempo. Suponiendo que Q sea independiente de la temperatura, se ob-
tiene una expresión que representada en escala semilogarítmica en función de $\frac{1}{T}$
da una recta cuya pendiente es $\frac{Q}{R}$; de aquí se puede despejar Q.

En nuestro caso hemos representado el lg. del tiempo necesario para al-
canzar 1/2 de la máxima propiedad.

Se ha realizado esto para dureza, conductividad, y fem. Los valores obte-
nidos son:

Q dureza   = 23,000 cal/mol
Q fem   = 25,600 cal/mol
Q conductividad   = 22,000 cal/mol

CONCLUSIONES

Se ha seguido la precipitación en aleaciones Cu-Zr utilizando dureza, conductividad, fuerza electromotriz termoeléctrica, dilatometría, rayos X y corte.

Se verificó que adiciones de 0.08% Zr elevan notablemente la temperatura de recristalización, existiendo probetas que permanecieron 250 hs. a 300ºC sin disminuir su dureza.

El máximo aumento de dureza se observa para envejecimientos de 5 min. a ºC. Aparentemente un solo mecanismo es responsable por el envejecimiento, no presentando las curvas isócronas de dureza más que un solo máximo.

Las probetas precipitadas presentan una estructura de Widmanstätten característica, que por analogía y dada su similitud con Cu Ti se supone que sea una fase Cu_3Zr ordenada e isomorfa del Cu_3Ti.

De las mediciones de parámetro de red se observó que la variación de la misma con la composición es muy pequeña ($<$ que 1×10^{-3} Å).

Las propiedades mecánicas son dependientes de la orientación y ésta dependencia es mayor cuanto mayor es el contenido de Zr.

La energía de activación de la precipitación se ha establecido en Q 23.000 cal/mol.

Para probetas solubilizadas, trabajadas 75% y envejecidas, las propiedades mecánicas son comparables y la conductividad es superior a las de Cu-Cr.

Por estas razones las aleaciones Cu-Zr presentan perspectivas interesantes dentro del campo de la industria eléctrica y de máquinas de soldar por resistencia.

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Tabla I.

Probeta Nº	% Zr
1	0,26
2	0,20
3	0,16
4	0,14
5	0,12
6	0,10
7	0,08
8	0,05
9	0,03

Fig. 1 - Contenido de Zirconio de las aleaciones preparadas
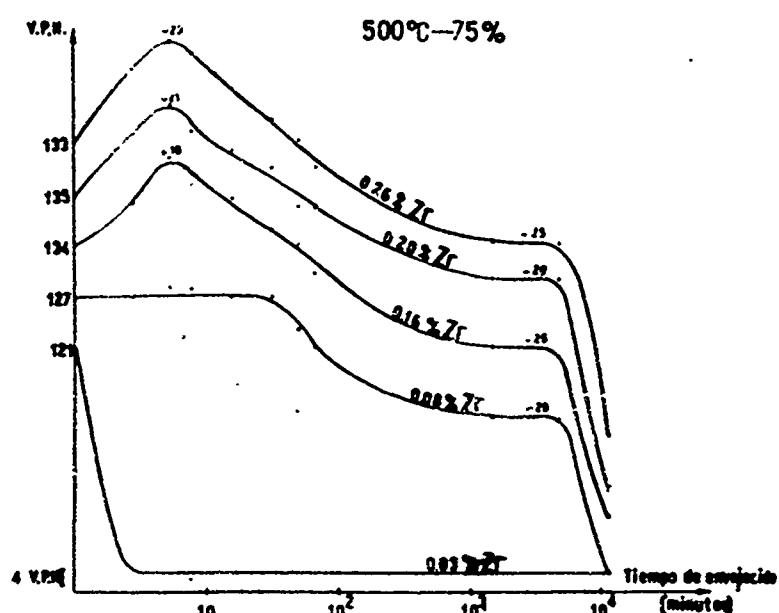
Fig. 2 - Variación de dureza Vickers en
función del tiempo de envejecido.
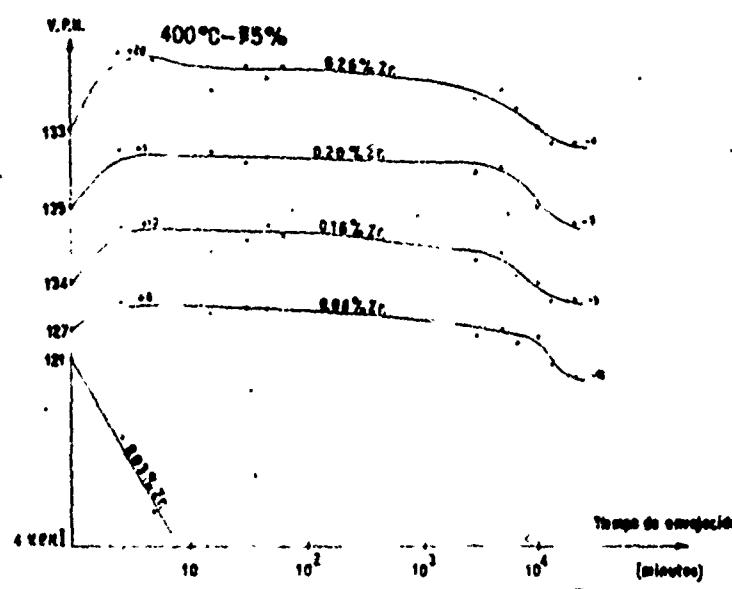
Fig. 3 Variación de dureza Vickers en función
del tiempo de envejecido
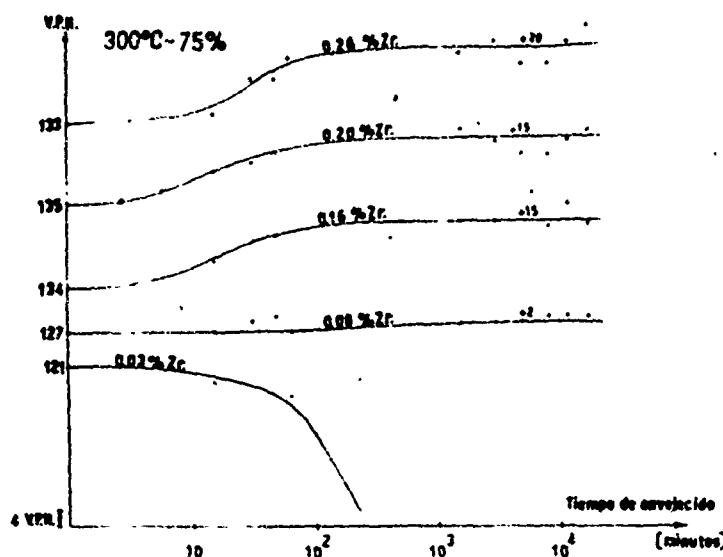
Fig. 4 - Variación de dureza Vickers en
función del tiempo de envejecido.
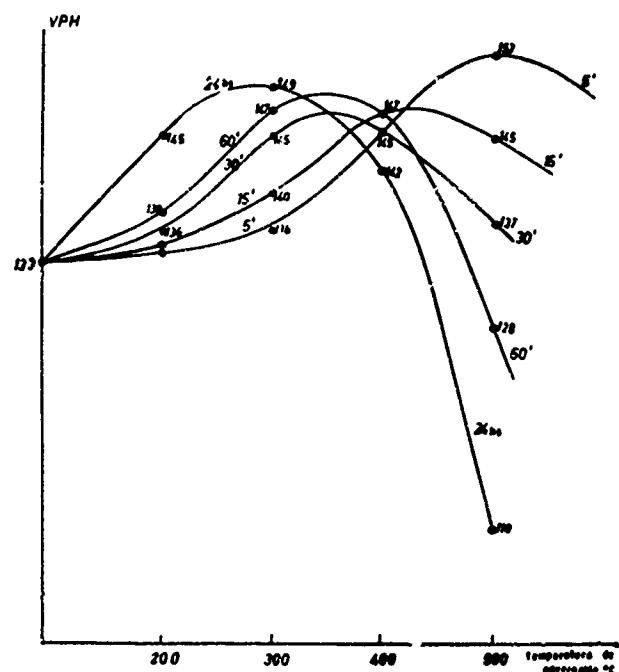
Fig. 5 - Isocrona de dureza para 0.16% de
Zr con 75% deformación

Fig. 6 - Pulido por tampón
Reactivo
amoníaco y agua oxigenada
2:1.   400x

Fig. 7 - Pulido por tampón
Reactivo
amoníaco y agua
oxigenada
2:1   850x
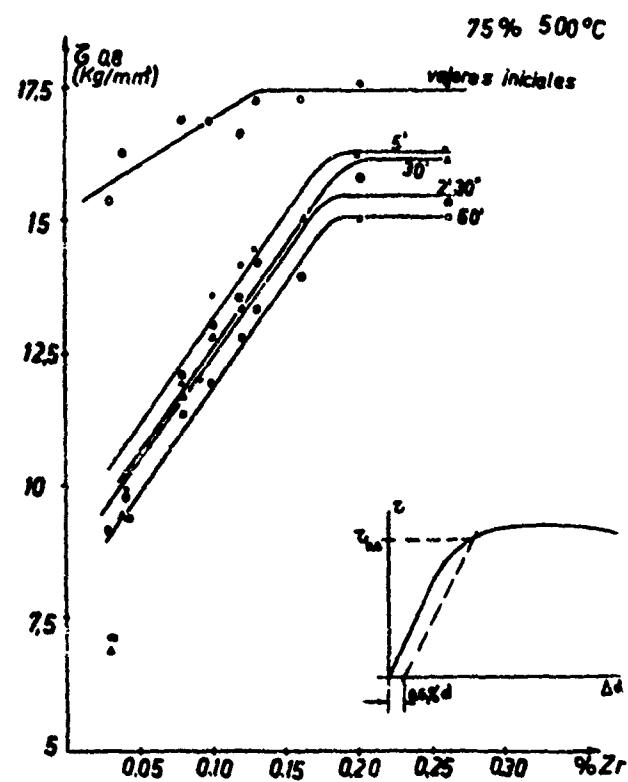
Fig. 8 - Propiedades mecánicas en función
de la composición para distintos
tiempos de envejecido
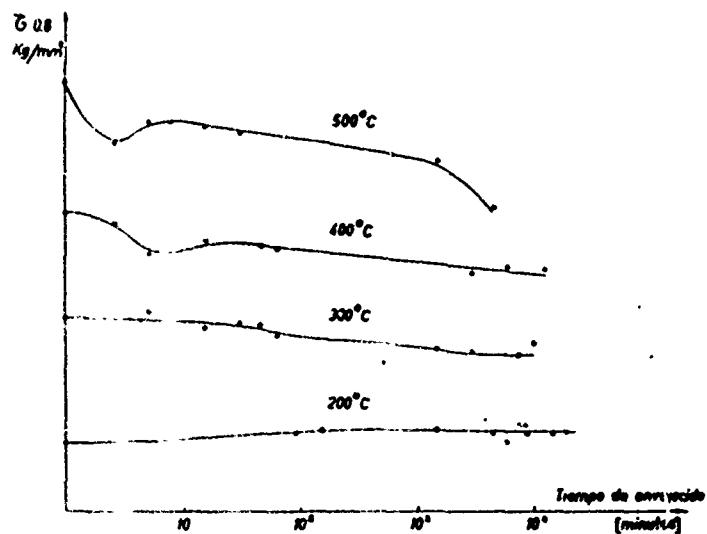
Fig. 9 - σ 0.8 vs. tiempo de envejecido a
distintas temperaturas para un con
tenido de 0. 16% Zr con 75% de de-
formación.
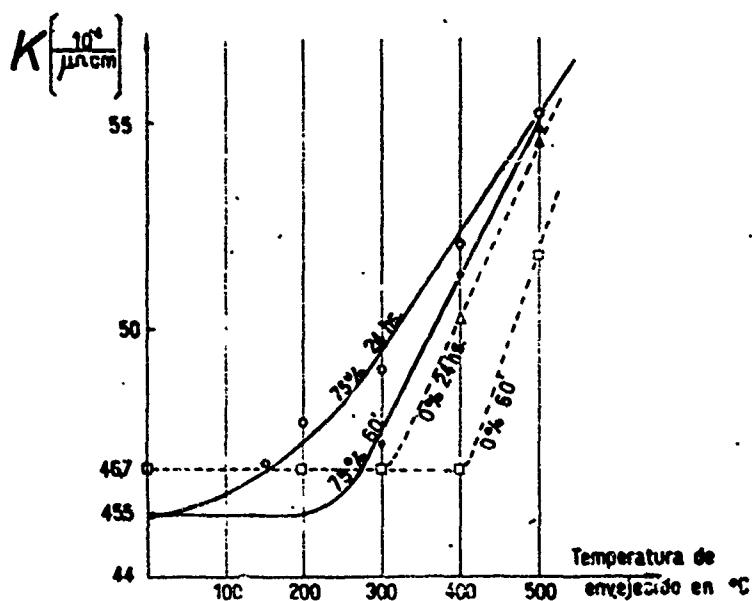
Fig. 10 - Isocronas de conductividad para
0. 16% Zr.
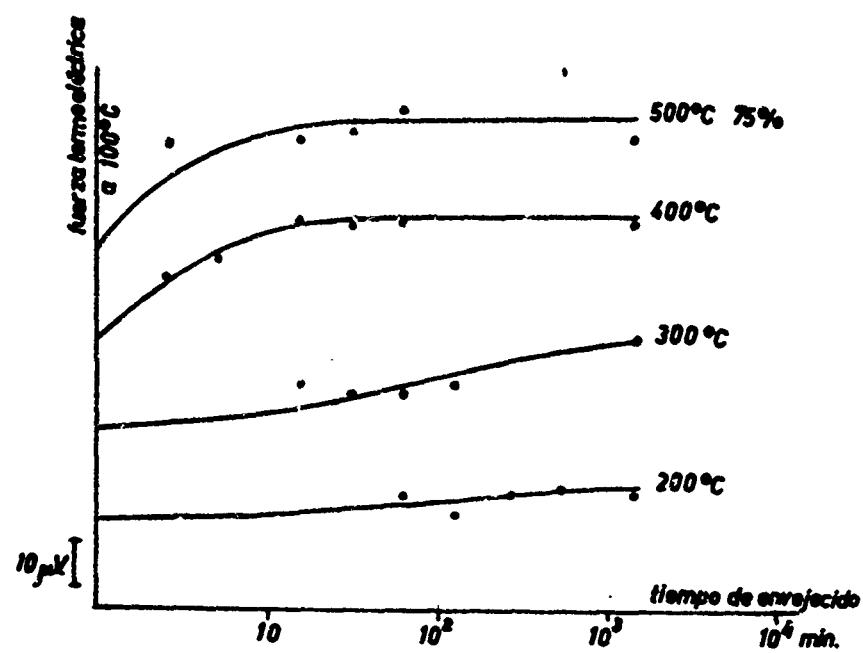
Fig. 11 - Variación de la fuerza electromotriz
termoeléctrica para probetas con
0. 16% de Zr.

NONFERROUS METAL SHEET MANUFACTURING

By F.R. Morral

Semicontinuous casting, casting of thin slabs, and powder metal-
lurgy are techniques used for producing sheet. Metallurgical char-
acteristics and mechanical properties are discussed. Use of these
techniques and related processes to manufacture sheet from
common metals and alloys and from unusual metallic materials
will be considered.

In companion papers, semicontinuous casting and casting of thin slabs of
steel are discussed, as well as the production of steel sheet by powder metallurgy.
Non ferrous metal sheet manufacturing follows these same principles, although the
details may be simpler. In some instances, semicontinuous and continuous casting
of slabs (the latter is also called "ingotless rolling") have proven advantageous
over the method of casting ingots, working by various methods to plate or slab,
then rolling to final size. The newer techniques are based on powder-metallurgy
processes; a few illustrations will be given.

It can be said that the art of continuously casting both ferrous and non-
ferrous metals has been developed to the point where any metal producer can
undertake it. Only a little imagination may be required to adapt the process to
more complex shapes. There are now about 50 variations of the process; however,
no attempt will be made to discuss these since they have been presented in many
articles and books[1]. Design of the unit and in-house construction should not pre-
sent difficult problems, since compact melting and working units are available.

There are few nonferrous metals and alloys that have not been continuously cast on a production basis. So far, continuous casting of nonferrous metals has resulted in avoidance of turbulence and oxidation, better distribution of constituents, fine grain, and less porosity. Considerable savings have been effected by avoiding excessive scrap due to shrinkage voids and other defects. In general, the physical properties of finished continuously cast nonferrous metals have been better and more uniform than those of metals conventionally produced.

There are essentially these techniques:

1. Withdrawal of the billet directly from the liquid metal from furnace or ladle

2. Continuously rotating mold (Hazelett, Properzi)

3. Casting into water-cooled mold -usually semicontinuous casting. Although the fully continuous process gives nearly 100 percent yield and steady, continued production, it has an initially high cost and requires considerable head room, since the molten metal must be raised to a high level. While the yield with semicontinuous casting is in the range 96 to 99 percent, the cost of the plant is less and the molten metal is poured from ground level. Changes in size and shape of casting are also easy in the semicontinuous process, since a new mold can be put onto the second unit while the first is being poured. In small-scale production, pouring directly from the melting furnace offers many attractions.

4. Roll casting (Bessemer, Hunter-Douglas).

Problems still requiring attention are:

1. Solidification at mold

2. Strength of metal near its melting temperature

3. Heat transfer from ingot to mold, which controls the rate of ingot withdrawal

4. Fluidity of the metal

5. Efficient design of the mold

6. Efficient conditions and design of secondary cooling zone

7.   Mechanism of formation of internal stresses in the ingot and means of reducing this detrimental effect

The advantages of continuous casting are:

1.   Average yield is high

2.   Lighter rolling equipment can be used since smaller   sections are cast

3.   Material quality is uniform and good

4.   The mill is capable of meeting, or being developed to meet, most requirements

5.   Little reheating is needed for immediate hot rolling.

Commercial Processes for Continuous Casting of Aluminum, Magnesium, and Their Alloys

In the United States, aluminum, magnesium, copper, and their alloys, and lead, zinc, tin, and nickel have been continuously cast for some years.

Several techniques are used to produce slabs 6 x 22 inches to 12 x 48 inches, with lengths up to 140 inches. That most used in America for aluminum is the ALCOA process, and in Germany, the equivalent VLW. These processes were developed between 1930 and 1940, and have also been used on brass with satisfactory results -sound slabs and surface quality. In both processes, the molten metal is controlled in a holding furnace before feeding into a stationary mold, or the metal is fed using electromagnetic pumping equipment. The plants are simple and economical and, although casting speeds seem slow in comparison with more elaborate plants, the advantages outweigh this one disadvantage. In one plant, there is complete integration -bauxite comes in one end, and aluminum sheet goes out the other.

The magnesium-type continuous-casting process is named for the company using it -Dow. Metal at about 1300 F (705 C) is pumped into the mold from 4,000-pound cast-steel pots. Virgin magnesium and scrap are charged into these pots and the mixture is heated to about 1400 F (760 C) for alloying and refining before casting. The pump is air-motor cooled. The mold, as short as possible, is made

of high-purity copper, although aluminum or magnesium could be used. It is encircled at the top and base with water-cooling rings. The top ring supplies a uniform film of water in downward streams over the mold exterior. The bottom ring directs water which assists that from the top ring and falls onto the cast product. Temperature and volume of the cooling water are carefully controlled. The whole unit should be on a rigidly supported base.

The Hunter-Douglas process for aluminum and its alloys is used particularly to produce aluminum sheet and strip and is also suited for foil. This is a horizontal continuous-casting process. Three Ajax low-frequency induction-melting furnaces, producing up to 6,000 pounds per hour, feed metal to two 20,000-pound gas-fired reverberatory furnaces. From open chutes in these furnaces, the metal is laundered to the casting machine. A constant and unbroken head of metal is maintained by means of an adjustable tap-hole valve. The mold in the casting machine is formed by two halves of a moving chain which consists of cast-iron blocks drilled for water cooling. As it leaves the endless chain, the metal has a temperature of 750-1000 F. After a 55-foot length of bar has been cast, a flying shear cuts it and it is rolled mechanically to a horizontal oven to be heated or cooled for hot rolling. Pinch rolls transfer the bar to a 6-stand tandem mill in which it is processed to 450-pound coils of 1/8-inch strip in about 60 seconds. The final operation is a cold reduction to gages between 0.0075 and 0.0092 inch with no intermediate anneals. Casting speeds run up to 15 feet per minute. The price of the caster, furnace, and auxiliary equipment is about $500,000. Licensing and royalties are also involved[2].

The Hazelett process has been suggested for aluminum, copper, brass, zinc, and steel. Molten metals poured between two belts are carried with them through the mill at speeds for aluminum of 27-35 feet per minute. Aluminum slabs 9 x 1/2 inch and strip up to 60 inches wide have been produced. It has been claimed that, with this process, stainless, silicon, and steel strip have been made with better properties than the same analysis rolled from conventional ingots. Now the cast metal strip is also continuously fed into a hot-rolling mill and then coiled (see Figure 1). The cost estimate for this equipment is nearly $1,000,000, including the caster, furnace, auxiliary equipment, licensing, and royalties[2].

Reynolds Metals Company recently announced a process for rolling sheet from pellets that could effect large savings in both plant investment and production costs. The new process operates continuously, produces a coil of sheet that may be of any length, and needs less equipment than a conventional rolling mill[3]. In contrast to heating and reheating large ingots, heat transfer to the small pellets is excellent, resulting in further savings in fuel costs. Pellets average 1/4 inch in length and 1/16 inch in diameter and must be free flowing. They are dropped through a vertical preheating furnace which brings their temperature to between

750 and 1000 F (400 and 540 C). Furnace time for each pellet is approximately 4 seconds, compared with several hours for an ingot. Hot pellets are fed between a pair of rolls where they are formed into a fully consolidated sheet. Thickness of sheet ranges from 0.1 inch down to foil gage. The company believes that the new process will have a significant impact on the aluminum-sheet industry.

A process suitable for aluminum strip and extrusion slugs is that developed by the Albert Mann Engineering Company, Ltd., of England. This consists of a rotary strip casting machine which produces up to 20-inch widths and permits easy changes in product size. The cost of the caster, furnace, and supporting equipment is quoted at about $250,000. A company to produce 6,000,000 pounds of aluminum product per year should be able to recover its investment within a year in the United States. Licensing and royalty arrangements are not required[4].

A machine best suited for bus bars and extrusion billets has been recently described by Ugine. Figure 2 shows the general arrangement for the Ugine-Venthon horizontal-casting process. Slabs 4 to 8 inches thick and billets 4 inches in diameter and larger are cast.

Powder-Metallurgy Techniques

H. Bessemer, in his autobiography, remarks that in 1843, while rolling fine brass turnings preparatory to making powder, the brass filaments tended to "issue from the rolls with a smooth continuous surface resembling an ordinary sheet of solid brass"[5]. Therefore, he may be considered the grandfather of this technique of producing sheet and strip from powders. During the past 15 years, many powder-metallurgy processes have been patented[6].

The mechanism of compacting metal powder by rolling has been reviewed in detail by Evans[7] and others. Evans describes the effect on the finished material of such important factors as the rolling mill (roll diameter, size of roll gap, surface finish of roll, rate of powder feed to the roll, and roll speed), the powder (grain and particle size), and sintering (temperature, time, and protective atmosphere).

Direct powder rolling is expected to be cheaper and more continuous than the use of the pressed and sintered form, which is then rolled (possibly hot) to a certain thickness and then cold rolled to final size[8].

The cost of manufacturing components by powder-metallurgy techniques can

be greatly reduced by the use of automatic methods which make continuous compacting possible. In a companion paper, some requirements have been outlined. For the production of sheet, it may be interesting to note that the process originally suggested by Sir Henry Bessemer for liquid metals can be used on powdered metals. Here the rolls are generally heated instead of cooled. The process of sheet-making consists of sintering after rolling the powders, and then re-rolling to finished size.

In the manufacture of very thin metal strip, the "direct rolling" of loose powders does, in some cases, have an economic advantage over the rolling of wrought metal. In direct rolling, powders are fed from a hopper directly into the throat of vertically or horizontally mounted rolls. The powders are carried by the surfaces of the rolls into the neck where they are compressed and finally ejected. It is well established that direct rolling of powder is most effective in producing very thin strip. A single pass through the rolls can provide 20- to 30-mil strip without difficulty.

Some aspects of direct rolling are not yet clearly understood. For example, much has yet to be learned about the effect on density and strip thickness of such factors as the diameter and pressure of the rolls, the shape and size of the powder, and the rate at which the powder is fed into the rolls. We have learned that the best product results when the diameters of the rolls are several hundred times the thickness of the strip and when powders of high green strength are used at moderate compression ratios (best to resist the stresses induced). By controlling these variables, densities up to 90 per cent of theoretical can be obtained for some metals in a single pass.

General factors affecting the sintering process are given in Table 1. Four types of factors must be closely considered -material (including source or method of making), particle size, compacting, and actual sintering. The sintered product may then be worked -hot or cold- to produce the final sheet or strip.

Continuous compacting of nickel, cobalt, copper, aluminum, and their alloys is a reality. This process merits much consideration if powder prices are low, if special properties are required, or only small runs are desired.

In 1958, Lund reported that the production of pure nickel strip by the continuous roll compacting of hydrogen-precipitated nickel powder, followed by suitable sintering and cold rolling, is practicable[9]. The mechanical properties of strip produced by this process are at least comparable to those of cast and wrought nickel in the same temper condition. Considerable amounts of this strip are now being coined into Canadian 5-cent pieces--truly "nickels"!

The process described below is a recent one, being used for nickel and

cobalt powder. The description is specifically of the production of cobalt strip on the rolling mill of the Sherritt-Gordon Mines Refinery in Fort Saskatchewan, Alberta, Canada.

Nickel and cobalt powders have a characteristically irregular shape. This appears beneficial in the production of a strong green strip on roll compacting. At Sherritt-Gordon, roll compacting is accomplished on a horizontally mounted unit so that the strip emerges vertically downward, is turned 90°, and wound into coils. The green strip is nominally 0.064 inch thick and 6-1/2 inches wide, with a theoretical density of 80-85 per cent that of the solid metal. The green strip is fed into a hot coiling furnace at 925 C. The sulfur content is lowered to 0.005 per cent and the carbon to 0.008 per cent by a moving hydrogen atmosphere, which prevents oxidation. When the strip is coiled in the furnace, the temperature is raised to 950 C. Hot rolling with a 25 per cent thickness reduction is followed by water-spray cooling and coiling under hydrogen atmosphere to prevent oxidation and discoloration. The density of the 0.048-inch thick cobalt strip is 8.72 g/cc (or 98.5 per cent of theoretical). The strip is annealed at 750 C after edge slitting and cold rolled 20 to 25 per cent in area. Annealing is done in bell furnaces at 930 C for 1 hour. The tensile properties are very sensitive to the procedure for obtaining tensile-test specimens and to the annealing temperatures[10]. In the case of cobalt, the close-packed hexagonal phase may be present, together with the face-centered cubic. It has been established that elongation values increase almost linearly, from 4 to 26 per cent, as the amount of cubic phase present increases from 7 to 50 per cent. Cold working affects the magnetic properties of cobalt, raising the remanence slightly and the coercivity considerably. Magnetostriction measurements agree with previously reported data.

Part of the reason for the improved properties may be the fine grain size, resulting from starting with fine powders. It is possible that, in some materials, the presence of oxides has a dispersion-hardening effect.

Sintered cobalt powders have been extruded in long bars with cross sections of varying complexity, and with densities close to 100 per cent.

The availability of cobalt strip opens new applications for this material such as anodes for electroplating and electroforming, memory tapes (because of high Curie temperature and other magnetic properties), tubing for inhomogeneous welding rods, bearings, and catalytic devices.

In general, the production of satisfactory sheet and other parts depends on factors indicated in Table 1. Table 2 gives data on sintering temperature and time for eight industrial elements and alloys.

Powder metallurgy is used to produce special sheet material, such as

dispersion-hardened nickel, known as TD-Ni (thoria dispersed in nickel). Experimental work has been done in which 5- and 10-mil fibers of tungsten have been embedded in cobalt powder; interesting properties at 2000 F (1095 C) have been obtained. (Metal whiskers could also be used). For these purposes, submicron powders both for "dispersant" and "dispersoid" are needed. To obtain the properties desired for TD-Ni, the mixture of powder has to be extruded. In fact, copper tubing is now under development and is believed to be economically feasible. The tubing made of copper powder seems to have unique features: greater toughness, improved formability, and higher yield strength. Reasons for these improved properties are not yet known. One contributing factor may be the dispersion-hardening effect of copper oxide particles.

There are three basic methods of extrusion: (1) direct extrusion of powders, (2) extrusion of pressed billets (as used for TD-Ni), and (3) extrusion of "canned" powder. The superalloy René 41 normally takes only 10-15 per cent cold work without annealing, but when starting with canned elemental powders, it is possible to cold reduce to 70 per cent. René 41 weld rods are made in this way.

Some alloys in the United States are available as powder. Another technique that has some promise is that of using precoated powders. Each grain (metal or nonmetal) is coated with a metal. In fact, individual grains can receive several different coatings of various elements. An interesting material is strip of a given porosity, such as may be used for plain bearings, filters, or air-permeable parts for pneumatic conveyors.

New technical properties can be imparted by the incorporation of certain additions to the metal powders before the sheet is produced (.e.g., the frictional properties of bronze parts are improved by additions of graphite).

Of course, to make sheet or strip of refractory metals -W, Mo, Cb, etc.- the powder-metallurgy technique appears to be the only feasible one.

There is not time here to compare mechanical properties of metal and alloy sheet and strip made by semi- or continuous casting, or powder metals made with the conventional methods of melting, casting, and fabricating. The purity of the materials involved, the amount of work given, and in some instances, the heat treatment, make comparisons of tensile strength meaningless. An example is given in Table 3 for nickel sheet produced by powder metallurgy. Table 4 compares the properties of 316 stainless steel and Inconel made by powder metallurgy versus conventional processes[11]. Table 5 gives properties for a nickel-base superalloy, Udimet 500. Note that the extrusion product by powder metallurgy has properties in excess of those of the wrought material.

Curtiss Wright reported that, in their processing of scrap to powder, the

the cost for the latter ranged from 17.8¢ / lb for a 10-ton/day plant to 8.3¢ /lb for a 100-ton/day plant[11]. Sheet processing costs were estimated at about 10¢ / lb for a 50-ton/day plant making various grades of stainless steel and 25¢ / lb for a 10-ton/day plant turning out specialty alloys. They concluded that cost analyses looked favorable.

Should Central and South American countries consider the metal-fabrication processes discussed in this and companion papers? The answer lies in the following questions:

1.   Is there a market or will there be one for materials or products manufactured by them?

2.   What are the sources and prices of raw materials?

3.   Can the equipment be produced in your country or must it be purchased from hard-money countries and imported?

4.   Do you engineers have ideas to simplify or adapt these processes to your own specific needs?

Although the first item mentioned is the most important, it is the last that holds the key to the success of any method adopted. The possible economic advantage of these new methods (semi- and continuous casting and powder metallurgy) is evident; however, this is true only if your creative ability can adapt them to your own specific requirements. Here again, today's creative planning can mean tomorrow's productive living!

TABLE 1. FACTORS AFFECTING SINTERING PROCESS

A. Material factors:

    Crystal structure
    Diffusion coefficient
    Melting point
    Density

B. Particle factors:

    Method of fabrication
    Particle shape
    Particle surface conditions
    Particle size

C. Compacting factors:

    Compacting pressure
    Compacting temperature
    Compacting speed
    Compacting atmosphere
    Duration of compacting

D. Sintering factors:

    Sintering temperature
    Time at temperature
    Sintering atmosphere
    Rate of heating
    Rate of cooling

TABLE 2. SINTERING TEMPERATURE AND TIME (IN HIGH HEAT CHAMBER)

Material	Temperature, C	Time, minutes
Bronze	760 – 870	10 – 20
Copper	845 – 900	12 – 45
Brass	845 – 900	10 – 45
Iron, iron-graphite, etc.	1010 – 1150	8 – 45
Nickel	1010 – 1150	30 – 45
Stainless steel	1095 – 1290	30 – 60
Alnico magnets	1200 – 1300	120 – 150
Tungsten carbide	1425 – 1480	20 – 30

TABLE 3. PROPERTIES OF NICKEL STRIP MADE BY DIFFERENT METHODS

Material	Impurities, %							UTS tons/ in.2	Elong % on 2-in Gage Length	Erichsen Test Value mm
	C	S	Fe	Si	Mn	Al	Mg	Cu			
Directly Rolled Nickel											
Soft*	0.01	0.001	0.005	0.005	0.005	ca. 0.01	0.005	0.005	24.4	19.0	8.91
Hard (64% reduction)	0.01	0.001	0.005	0.005	0.005	ca. 0.01	0.005	0.005	36.5	1	3.10
Conventionally Made Nickel											
Soft*	0.04	0.002	0.1	0.05	0.03	--	0.1	0.1	24.1	20.0	9.35
Hard (38% reduction)	0.04	0.002	0.1	0.05	0.03	--	0.1	0.1	44.3	1	4.50

*Materials annealed under conditions to give a grain size of about 0.02 mm. Directly rolled nickel annealed for a nominal period of 30 sec. at 700 C; conventionally made nickel annealed for a similar period at 925 C.

TABLE 4. HOW POWDER STRIPS COMPARE

| | Rolled 316 Stainless Strip[a] | | Rolled Inconel Strip[b] | |
	Powdered	Commercial	Powdered	Commercial
Room-Temperature Properties				
Yield strength, psi	46,800	29,900	34,200	30,300
Ultimate tensile strength, psi	101,000	78,900	90,550	84,410
Elongation, per cent	38.3	59.9	25.2	30
Hardness when heat treated, R_c	--	--	--	--
High-Temperature Properties				
Time to rupture (in air at 1500F under 10,000 psi load), hours	--	--	9.8	6.2
Corrosion Test				
Boiling 65% HNO_3 for 96 hours	7.5 mils/yr	8.6 mils/yr	--	--
Interstitials				
Carbon	0.07 %	0.05 %	--	--
Oxygen	0.05 %	0.01 %	--	--
Nitrogen	220 ppm	535 ppm	--	--
Hydrogen	17.4 ppm	12.7 ppm	--	--

(a) Annealed at 2025 F for 30 minutes
(b) Annealed at 1800 F for 30 minutes

TABLE 5. PROPERTIES OF UDIMET 500 POWDER-METAL EXTRUSIONS
(Heat Treated)[a]

Specimen	Tensile Strength, 1000 psi	Yield Strength (0.2% offset), 1000 psi	Elongation, %
1	199	143	11.8
2	193	144	9.0
Typical[b]	175	110	15.0

(a) Solution treated 4 hours at 1975 F, air cooled; then aged 24 hours at 1150 F, air cooled; then aged 16 hours at 1400 F, air cooled.
(b) Properties reported in Utica Metals Bulletin. Source: Toaz, Davies, and Johnson, "Aircraft Superalloys by Powder Metallurgy", Progress in Powder Metallurgy, 152, 16, 1960.

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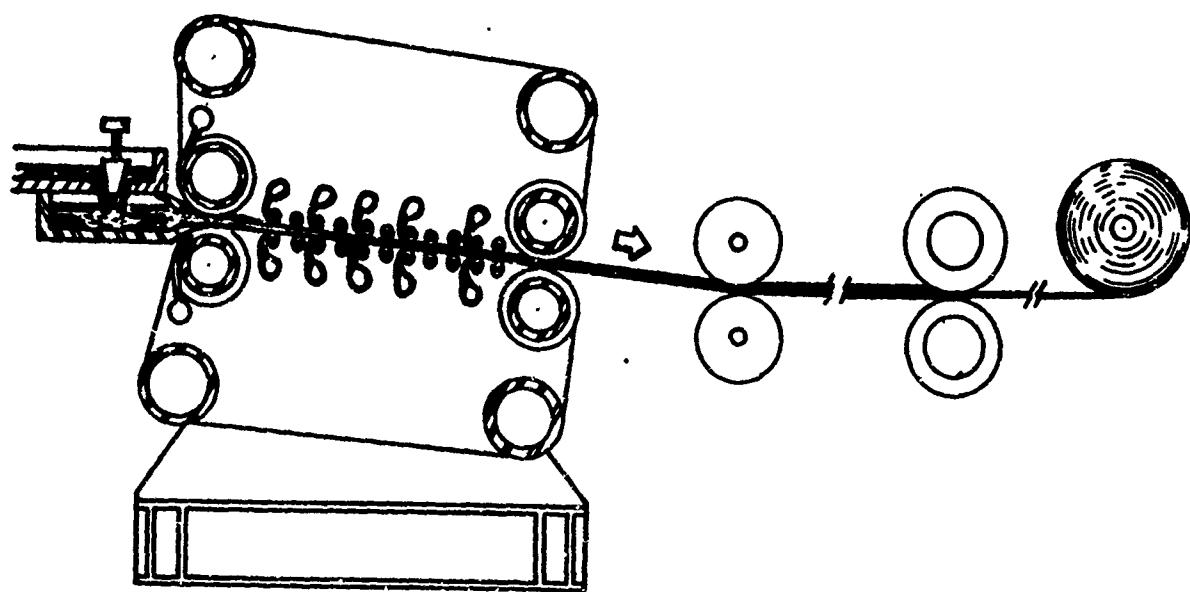
Figure 1 Hazelett Strip-Casting Process
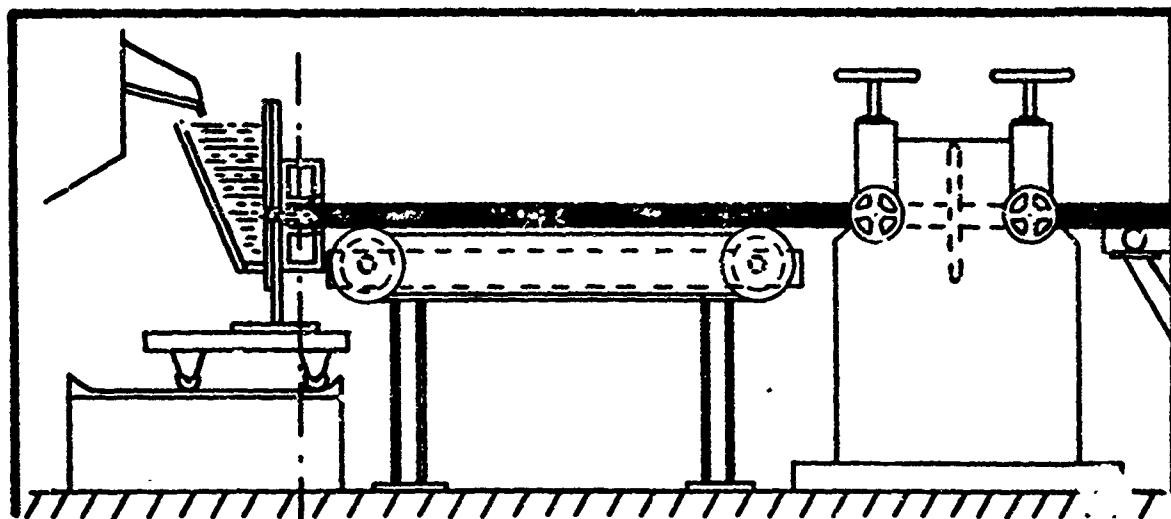
Figure 2 General Arrangement of the Ugine-Venthon Process for Horizontal Casting

DESIGN OPTIMIZATION THROUGH MATERIALS RESEARCH

by

M. A. Steinberg

1. NEW METHODS IN MATERIALS RESEARCH

The traditional viewpoint in materials applications has been to cleverly adapt (and sometimes compromise) a design concept to the unyielding properties of the materials available, to cut and pare performance goals to the size of the often ill-fitting mold of conventional materials. In the aerospace field, as new and more demanding missions present more and more stringent requirements to the materials engineer, this traditional approach has had to be modified. Now materials men are faced with the problem of designing "to order" entirely new materials or combinations of materials with properties suitable to meet service conditions within the time schedule for system development. Materials are "tailor-made" with an end-service orientation, and each application may have its own unique solution with respect to materials and design.

We may characterize the older design procedure as linear, that is, it proceeded stepwise from known properties of proven materials, forced modification of preliminary design to suit materials available, and, through a trade-off process, resulted in a final design adapted to use of pre-existing materials. The newer procedure makes use of a more simultaneous method of attack. From extrapolations of properties of existing materials or combinations of materials, materials requirements are set at the initiation of a project. Then the researchers turn their efforts to satisfying these requirements while other elements of systems design are progressing. The complexity of materials problems in the aerospace industry stems from the fact that these requirements combine exacting and often unusual combinations of properties with short lead-times for research and development. Major difficulties arise because design concepts and critical environmental factors are still foreign to most members of the materials field.

The problem is further complicated by an incomplete or erroneous understanding of the basic properties and capabilities of new materials on the part of the user -- the design engineer. Close coordination between the activities of structural designers and materials specialists is essential to any materials research and development program. A harmonious working arrangement is necessary among producers, users, and government sponsors in planning and timing for future needs.

The transition from conventional aircraft construction to missiles and spacecraft characteristic of the past decade has spurred the development, through the "simultaneous" processes mentioned above, of high temperature structural materials as well as a number of newer developments in the fabrication of light-weight structures.

Weight is at a premium in every endeavor in this industry. Structures must be designed to the lightest possible weight at a supportable cost and equal to the capabilities of all of the other components of the system -- the power plant, guidance controls, propulsion, and payload. To accomplish this, the materials engineer must know the real value of each pound saved as well as knowing how material, fabrication, and installation costs vary from material to material.

Misleading results can be obtained in design optimizations for minimum weight if improper comparison parameters are used. W. R. Micks of Rand Corporation (Ref. 1) gives an example of this in a comparison of two materials for use in a narrow column. With given dimensions for a square cross section tube, a column of A Z31M magnesium (FS-1H) has a buckling strength of 2500 pounds. When a column of 7075-T6 aluminum is designed to the same weight, length, and cross-section proportions, the failure load for this equal-weight aluminum column is found to be only 1730 pounds.

Taking these facts, however, to mean that magnesium is 1.44 times as efficient, on a weight basis, as aluminum is erroneous, as Micks points out. In the first place, the geometric proportions of the aluminum column should not have been made the same as the magnesium, since the optimum aluminum column would have different proportions. When this error is corrected, the ratio of magnesium to aluminum strength now appears to be only 1.28. These comparisons are shown in the first three bars of Fig. 1.

A further error in the comparison is that the wrong parameter is being used for comparison. Strength, which the designer does not want to maximize, has been chosen instead of weight, which he does want to minimize. The strength is assumed to be a constant requirement of the mission with the weight to be made as small as possible. If an optimum aluminum column is designed to have the same strength as the magnesium column, the ratio of aluminum weight to magnesium weight is 1.13 as shown in Fig. 1.

To illustrate further how the comparison depends on the proper specification of the design, if the structural job, as measured by the ratio of the design load to the square of the effective pinned-end length over which the load is transmitted, is changed from $P/L^2 = 1.0$ psi to $P/L^2 = 100$ psi, we find that the relative efficiencies have been reversed, as shown in the right-hand bars of Fig. 1.

This example of design optimization depended on a proper comparison between properties of available materials. The more usual case is likely to involve requirements for materials properties which cannot be immediately met by any

available commercial material. The approach to this problem is an optimization study, as is done in systems work. Such a study is undertaken at the very beginning of a program in the generalized design or system study where the materials characteristics required are determined in terms of the relative importance to the need. This then delineates the level of materials research and development to be supported so that, in the development of the system, needs will be fulfilled in the proper time-scale position.

Thus, materials engineering is vitally concerned with preliminary design, a point worth dwelling on, since, to me, it is the one which differentiates the interdisciplinary approach to materials science from materials engineering.

In the broadest sense, materials engineering is intimately interwoven with mechanics (including mathematics), thermodynamics, aerodynamics, and structures, as well as with electronics or solid state physics. It is the close relationship in these fields that makes materials engineering a true engineering entity.

In fact, the linking of "feedback" is much stronger in these interdisciplinary fields than it is with physics of solids, or structure on an atomistic scale. It is from his fellow engineering colleagues that the materials engineer first gets a look at the environment problems that his materials will be faced with, and under which conditions they must operate. In general, the requirements are such that, in their delineation, a real language disability between materials specialist and the engineer (not designer) in the analytical fields can exist until one completely understands the other. Only when such a gap is bridged can innovations arising from materials science of elsewhere be brought to useful end-item hardware.

Obviously, research cannot be done on every material. Micks, of the Rand Corporation (Ref. 2) has recently written about materials engineering in the systems concept, delineating a number of steps to help decide which direction materials R & D should take to meet the material demands of a new major weapons system. He has suggested using the generalized design or systems study -- the method of operation for the preliminary designers or advanced system study engineers -- for determining the actual materials research and development to be conducted, and has indicated the steps shown in Table 1.

Utterly confusing to a materials engineer is to embark on a materials program for end-item application only to have the parameters change, causing a need for a continuously varying materials input for the end-item. Again, Micks has drawn up relationships to use as a guideline. Table 2 presents the kind of information with which a materials engineer and the aerothermo-structures researcher are constantly embroiled in satisfying the systems engineer or designer.

Many examples could be given of the tailor-making of materials or materials combinations to the requirements dictated by missile or spacecraft systems requirements. A few of these examples will be outlined later to show how this principle of "materials designed to order" applies to a wide range and variety of

Table 1

STEPS TO EVOLVE AN R & D MATERIALS PROGRAM FOR A MAJOR WEAPONS SYSTEM (Ref. 2)

1. Form the initial concept and advanced design of the system.
2. Determine how materials capability influences the end-item capability.
3. Derive from these interactions the information that is relevant to materials R & D planning.
4. Derive from this information the appropriate research directions and goals.
5. Form research and development programs that properly reflect these research directions and goals.
6. Judge and decide which programs to implement and at what relative levels of effort.
7. Conduct the actual research and development activity.

Table 2

PARAMETRIC ANALYSIS OF COMPONENT AND MATERIALS CAPABILITIES AGAINST MISSION CAPABILITY (Ref. 2)

1. Which vehicle components are the most important in determining the overall vehicle capability?
2. What are the most important materials parameters affecting the design of these components?
3. What ranges of parameter values are of interest?
4. In what range of parameter values is the greatest improvement obtained in the vehicle capability as a result of incremental improvements in the materials?
5. What are the relative payoffs for the various materials improvements?
6. What minimum improvements in the materials are necessary to provide an interesting improvement in the end-item?

types of materials. Possibly one of the most important such examples of this process in action is the design of thermal protection materials for reentry systems to which much work has been devoted in the past few years.

2.   THERMAL PROTECTION MATERIALS FOR REENTRY STRUCTURES

The success of the many aerospace programs is dependent on the development of lightweight high temperature structures. To consider the problems involved in the design of high temperature structures, the following questions must be posed:

*   Where may these configurations be applied?

*   What is the minimum weight consideration?

*   What materials are compatible with the design environment?

*   Which methods of analysis are reliable in lightweight high temperature structural design?

2.1.   Basic Concepts of Reentry Vehicles

One of the environments that is of interest for the large majority of high temperature applications in the aerospace field is reentry. Spacecraft entering from orbital and superorbital trajectories encounter severe heat pulses as well as maneuvering and deceleration loads. The conventional approach to the structural design of such vehicles is a load-carrying metallic structure with heat blocking materials provided where necessary. Re-use of such structures is, in most cases, not possible.

The aerodynamic heat input to a reentry structure is expressed as an instantaneous heat flux ($\dot{q}$) in Btu/ft^2 sec and a total heat input (Q) in Btu/ft^2. From a materials requirements standpoint, the instantaneous heat flux ($\dot{q}$) and the duration of the heat pulse are the most important considerations. These determine the optimum thermal protection system and the required materials characteristics. The maximum temperature attained depends to a large extent on the heat flux and the surface emissivity. High values of total heat input (Q) are not necessarily critical, since this is a time-integrated function. Most of the total energy can be stored or dissipated by the system.

The following two approaches are used in the design of thermal protection

systems for reentry structures:

* Absorptive Systems -- heat flux is accommodated by mass-transfer heat absorption (ablation) or by storing heat during exposure (heat sink).

* Radiative Systems -- heat is dissipated to the atmosphere by radiation from a hot surface.

Absorptive systems usually are limited by weight considerations to short-time use and are best suited for very high heat flux ($\dot{q}$ = 2000 Btu/ft^2 sec). Radiative systems are limited by melting points of heat shields and structures to relatively low heat fluxes ($\dot{q}$ = 200 Btu/ft^2 sec) for long-time use or to higher fluxes for short-pulse heating cycles. Either of these methods, or a combination of both methods, may provide the optimum system for a given vehicle.

Reentry vehicles (Fig. 2) are divided into three major classifications based on the escape velocity at the start of reentry: (1) suborbital (1800 to 24,000 fps), (2) orbital (24,000 to 26,000 fps), and (3) superorbital (36,000 fps). The ballistic missile nose cone is the most familiar example of a suborbital vehicle.

Peak heating rates ($\dot{q}$ = 1200 to 3000 Btu/ft^2 sec) are the highest for any class of vehicles, but the maximum heat pulse duration is short (1 min). Total heat input ranges from 10,000 to 30,000 Btu/ft^2. Ablative and heat-sink materials are used widely in these structures.

Orbital vehicles, such as existing manned and unmanned reentry capsules and boost-glide vehicles, sustain the lowest instantaneous heat flux ($\dot{q}$ = 200 to 500) over a much longer duration than those of ballistic reentry vehicles. The total heat input is similar to that for ballistic reentry, depending on the range. As previously mentioned, radiation cooling with insulated structures and heat shields provides the most efficient method of thermal protection for these vehicles.

Superorbital vehicles that must reenter the earth's atmosphere on return from a space mission present one of the most critical problems in thermal protection. Instantaneous heat fluxes approach those for ballistic reentry ($\dot{q}$ = 200 to 1100 Btu/ft^2 sec) and must be sustained for long time periods. The total heat input (Q = 50,000 to 300,000 Btu/ft^2) is highest for any class of vehicles. A combination of absorptive and radiative thermal-protection systems will most likely be required.

A typical mission flight corridor for a winged reentry vehicle with a specific W/C_dA is shown in Fig. 3.

Within each class of reentry vehicles, considerable variation in materials requirements is met, depending on vehicle design and nature of the flight.

2.2.   Materials Considerations

As an illustration, let us consider the process of defining materials re-
quirements for reentry vehicles, specifically those vehicles that do not have spe-
cific lifting and control surfaces such as wings and fins, and which are character-
ize by a lift-to-drag ratio of less than 0.5. Design of this class of vehicles would
first of all be governed by the environment as generally described in Fig. 2. Next
the complete range of environments likely to present problems must be examined
for the subsystems of interest. For these reentry systems the aerodynamic
thermal environment is likely to be a severe problem for heat shields, radomes,
insulation, and sealants and a lesser one for primary load-bearing structures and
internal structures. The solar thermal environment as well as solar and nuclear
radiation will also adversely affect radomes and transparencies. Stresses due to
static, cyclic, acoustic, accelerative, and thermal factors will likely be a problem
for heat shields, load-bearing structures, and to a lesser extent, radomes and
sealants. Insulation would not be affected. Impingement phenomena (meteoroids,
sputtering) should affect only the heat shields and radomes. High vacuum is not
likely to be a problem for any of these sub-systems. Nuclear radiation adversely
affects heat shields, radomes, and sealants.

Based on this environment, we must then attempt to determine the most
important parameters governing the various subsystems of this type of vehicle.
Table 3 shows those properties which have been judged to be of primary and
secondary significance for reentry vehicle performance. Having determined the
significant properties we next specify the ranges, if known, over which these pro-
perties may vary.

A complete specification would include the range of properties required for
all the materials to be used in the system, based on the expected environments to
be encountered.

Once the required materials have been described as completely as possible,
the design of optimum materials to meet these requirements can proceed. Two
examples will be given here of thermal protection materials developed for reentry
structures -- a thermal protection composite for heat shields, radomes, etc., and
coated refractory metals for leading edges of lifting hypersonic vehicles, etc. The
first example is that of Lock-Heat, a family of composite materials for thermal
protection systems based on inorganic bonding of various refractory fibers, de-
veloped by Lockheed Missiles & Space Company. The material system can be
modified for each application, to encompass a wide range of physical and thermal
properties.

The fabrication process possesses great versatility in the placement of the
various strata, i.e., the structure, insulation, porous refractory skeleton, and
ablative-loaded refractory skeleton may be fabricated in any sequence. Moreover,
the types and amounts of the various ingredients can be adjusted to provide optimum
performance for minimum weight and most significantly they can be tailored to
specific design requirements.

Table 3

SIGNIFICANT MATERIALS PROPERTIES AFFECTING REENTRY VEHICLE PERFORMANCE

Heat Shields

Ultimate Strength
Yield Strength
Ductility
Stress Rupture
Toughness
Conductivity
Specific Heat
Emissivity and Absorptivity
Effective Thermal Capacity
Melting, Boiling Points
Corrosion Resistance

Primary Structure

Ultimate Strength
Yield Strength
Elastic Modulus
Toughness
Oxidation Resistance

Internal Structure

Yield Strength
Elastic Modulus
Toughness

Radomes and Transparencies

Ultimate Strength
Elastic Modulus
Dielectric Constant

Insulation

Conductivity

Sealants

Ultimate Strength
Elongation
Creep

The properties requirements are given below for one of the subsystems of Table 3.

Ablative Shields

Key Requirements:
 Heat of Ablation $(q^*) = 15,000$ Btu/lb
  (does not include re-radiation)
 Structural integrity at reactive temperatures
 Low thermal conductivity
  $(< 0.8 \times 10^{-5}$ Btu/hr-$^\circ$F-ft)

Environmental Conditions:
 Space environment: 1 to 100 r/hr dose rate
 Meteoroids: bombardment at velocities up to 72 km/sec up to 4000 km altitude
 Entry environment: high heating rates $(> 2000$ Btu/ft^2-sec)

Applications of interest with the Lock-Heat design capability include heat shields for missile and satellite reentry, radomes for high temperature use, exit cones for rocket motor components, and insulation of rocket components. Radar cross-section reduction and vulnerability reduction are obtained through controlled energy absorption. Figure 4 shows the backface temperature response of a Lock-Heat composite exposed to long time heating.

For radomes on missiles and spacecraft, the high thermal loads associated with reentry require both ablative cooling for high intensities and insulation for long soak times. A noncharring ablator is to be incorporated in a thin outer shell, while insulation will be provided by an inorganically bonded fibrous quartz network of fairly low density. The dielectric constants of the inner and outer shell will be balanced to a particular ratio prescribed by electromagnetic design considerations for the two frequency ranges to be transmitted. This approach is believed to be unique in current radome designs. Further applications of this versatile technique can be expected in the future.

A summary of mechanical properties determined for a specific Lock-Heat formulation is presented in Fig. 5, indicating modulus as well as tensile and compressive strengths at room and elevated temperatures. It is immediately obvious that Lock-Heat possesses certain physical properties at elevated temperatures which cannot be achieved by homogeneous materials. Consequently, under some circumstances, Lock-Heat materials can be considered for use as load-bearing structures and can also provide for mechanical attachment to substructures.

Refractory metals and alloys will be used most extensively in high supersonic and hypersonic cruise and hypersonic boost-glide or reentry vehicles. Limited local applications will be made in certain types of missiles and boosters. Development of these metals is required in the material forms and possessing the properties indicated under environments specified below.

The materials will be used on supersonic and hypersonic cruise vehicles and hypersonic boost-glide and reentry vehicles on their lower surfaces, loading edges, and nose cones under conditions of heat flux ranging from 5 Btu/ft^2-sec to as high as 200 Btu/ft^2-sec. The corresponding materials equilibrium surface temperatures will range from 2000 to 4500°F. Exposure times will range from 300 hours at 2000°F to 25 hours at 4500°F. Transient heat fluxes as high as 16,000 Btu/ft^2-sec will be experienced on the nose and leading edges of high performance missiles.

Coated refractory metals may be used for these applications and for portions of the structure adjacent to the nose. However, the short-time duration of the heat pulse will tend to favor the use of ablatants. Some conditions which will influence designs and choice of materials are:

* Maximum loads will not occur at the same time as maximum temperatures.

* Fatigue, creep, and stress rupture from cycling temperatures and stress will be critical in design.

* Acoustic levels of 165 to 185 dB at the power plant to 205 dB on the surfaces will occur at high speeds and low levels.

The material forms required will be sheets less than 0.060-in.-thick, sandwich structures in foil gages $\sim$ 0.005 in.; extrusions may be required for low altitude cruise vehicles. For fastening and joining, welding and brazing will be favored but mechanical fasteners will also serve. There will be little use of castings, but forgings, weldments, and pressed and sintered parts will be used at local strong points (Ref. 5).

Properties that are required in these materials are good ductility, resistance to crack propagation, stress corrosion, and weldability. In addition, these materials must have good oxidation resistance or compatible coatings must be available for protection from low partial pressure oxidation. Besides the pure metals, alloys with good formability and which can be resistance-welded should be developed. Some desirable properties are elongation greater than 4% and ductile-to-brittle transition temperature less than - 100°F.

Because of the long heating times and heat flux levels encountered, special materials problems exist at the leading edges of the aerodynamic control surfaces (nose, wings, and fins). If a refractory material is considered, it is readily found that radiation cooling results in radiation equilibrium temperatures which can easily exceed 3500°F, a temperature regime which is much higher than can be tolerated by all but a very few materials.

Because of the high temperatures produced at the leading edges of control surfaces of hypersonic lifting vehicles and their sustained flight of an hour or more through the earth's reentry corridor, the penetration of the heat into the interior of the thermal shield and oxidation of the surface can occur. These conditions present problems in materials selection and design for these structures. The backface temperature of the heat shield must remain sufficiently low so that there is little danger of thermal failure of the attachments and the supporting structure. The material must resist surface oxidation which could cause shape changes that would alter the aerodynamic characteristics of the control surfaces (Fig. 6).

Success in using coated refractory metals requires careful matching of design features, manufacturing sequences, and service requirements to the characteristics of available coating systems. No one system has universal applicability since many factors other than temperature govern the basic performance and useful life of coated parts. Experience in the aerospace industry has shown that adequate reliability can be achieved in the scale-up of coating systems from the laboratory to production hardware. However, this can be done only within the performance capabilities of a given system as established in relation to a specific design and end-item use. Even the best of coating systems has an imposing number of limitations with respect to design, manufacture, and use. Most of the problems in using coated refractory metals result from a failure to recognize and design within the basic performance capabilities and inherent limitations of these materials.

The available performance data for specific coating systems are difficult

to evaluate due to lack of standardized testing procedures. Although coating com-
positions are standardized, uncontrolled variations in specimen geometry, spe-
cimen preparation, coating thickness, and testing conditions have produced a
somewhat confusing picture of performance capabilities. Although the situation
has improved considerably in the past year, a vast amount of work remains to be
do to accurately and adequately characterize these materials. Available in-
formation should be treated in generalized terms and should not be considered
as design criteria.

The major limitations in the use of coated refractory metals arise from
variations in the basic factors that control useful life and mechanical properties.
The more important of these factors are operating temperature, effective coating
thickness, effective substrate thickness, and atmospheric pressure and composi-
tion.

The relation of coating life to temperature and initial coating thickness
and the similarity in average life of all silicide-base coating systems suggests
that a common factor controls overall performance. Studies of $MoSi_2$ coatings
on molybdenum at Lockheed Missiles & Space Company have resulted in a new in-
terpretation and more complete understanding of coating behavior that may provide
the key to the problem of predicting coating life. It now appears that useful life
may be governed by the time required to convert the coating from the higher sili-
cide ($MoSi_2$) to the next lower silicide (Mo_5Si_3) by diffusion.

Figure 7 indicates this change taking place as a function of time at elevated
temperature (Ref. 6). The predicted lifetimes of $MoSi_2$ coatings are shown in
Fig. 8 (Ref. 7).

3.   THE GLASS FILAMENT-EPOXY RESIN ROCKET
      MOTOR CASE

The factors involved in selecting the overall design features of a rocket
motor for a specific missile function are established at the time the missile sys-
tem is conceived. The requirements are based on the state-of-the-art and its
projected growth throughout the period of motor development. In transforming
target values into reliable engine components, sound judgment is the key in de-
ciding when advanced technology can be incorporated into an operational system.

Once a choice of propellants has been made, the motor case and inert
parts (nozzles, liners, and insulation) necessary to give minimum weight and re-
liability can be analyzed and the size and scope of the supporting development
program measured to make sure that the projected values of strengths, and hence
weights, are realistic in terms of deliverable hardware.

Let us consider a solid propellant rocket motor development for a missile
system designed in 1960 to be operational in 1965, projecting 1960--1965 growth
in terms of state-of-the-art and improvements in one area: the motor case (Ref.
4). The motor cases of interest are complicated by a number of off-center open-
ings, i.e., for thrust reversal, nozzles, and igniters. Based on projected
weights required and money available for development, of what material should
we make the case and of what magnitude should the development effort be?

Initially, the rocket industry made solid propellant motor cases out of steel.
As increased performance goals demanded lighter weight cases, steel case
strengths were increased, and the lower density high-strength titanium alloys
were given serious consideration. Finally, still lower density glass-filament-
wound cases came into use. Motor cases of these three structural materials were
analyzed in relation to their 1960 strength and weight. Forecasts of expected im-
provement in the state-of-the-art were made and considerations other than strength
and weight (i.e., cost) which were expected to influence selection of a structural
material for an advanced solid-weight propellant motor case were also evaluated.

Improvements expected in 1960 for incorporation into production hardware
by 1964 and beyond are shown in Fig. 9. The projected values are presented on a
strength-index basis. The strength used is the membrane hoop stress developed
in the cylindrical section of a motor case as a result of the proof hydrotesting of
each chamber. The strength index is the value obtained by dividing the stated
strength value by the density of the structure. All values presented are for
chambers without thrust reversers, and some weight penalty will be necessary for
chambers with thrust reversers in a forward dome.

3.1. Filament-Wound Glass

A 1960 index for glass of 0.858×10^6 was obtained from the then current
proof hydrotest stress of 60,000 psi, the then current density of 0.070 and glass
filament strength of 250,000 psi, and a burst factor of safety of 1.25. A 1961
index of 0.943×10^6 was obtained from an improved proof hydrotest stress of
66,000 psi (reflecting improvement in winding inefficiency factor from 43 to 14%)
and the same values of the other parameters. Without additional reduction of
winding inefficiency factor, a 1964 index of 1.058×10^6 is obtained from an im-
proved proof hydrotest stress of 76,000 psi (resulting from an improved glass
filament strength to 270,000 psi and a reduced burst factor of safety of 1.20) and
an increased density of 0.072. A 1966 index of 1.097×10^6 is obtained from an
improved proof hydrotest stress of 80,000 psi (resulting from a further improve-
ment in filament strength, some improvement in winding efficiency with such
improved design concepts as large, single-end openings with winding terminating
short of the polar region, and use of large metal inserts of reduced weight and
reduced burst factor of safety of 1.176) and an estimated density of 0.073.

The projected strength-index values are plotted in Fig. 9 for the years in

which production glass cases are expected to be ready for use with propellant.

3.2.   Titanium

A 1960 index for titanium of 0.776×10^6 was obtained from the 135,000 psi heat-treated yield strength currently being produced with the 6 Al 4V alloy with a 1.25 yield factor of safety (proof hydrotest stress 124,000 psi) and the 0.160 density of this alloy. A 1961 index of 0.915×10^6 was obtained from an improved proof hydrotest stress of 160,000 psi attainable with the B 120 VCA alloy at a yield factor of safety of 1.15 and the 0.175 density of this alloy. The reduced yield factor of safety was projected on the basis of an expected improved product reliability. A 1964 index of 1.075×10^6 is obtained from an improved proof hydrotest stress of 188,000 psi (resulting from an improved heat-treated yield strength of 180,000 psi now being developed and expected to be in production use in 1964, and a further reduced yield factor of safety of 1.10) and the 0.175 density of the B120 VCA alloy. A 1966 index approaching 1.1×10^6 is hopefully anticipated with a slight improvement in proof hydrotest stress to 192,500 psi (resulting only from an improved heat-treated yield strength without further reduction in the yield factor of safety). The density is unchanged at 0.175. These strength-index values are plotted in Fig. 9.

3.3.   Low Alloy High Strength Steel

A 1960 index for steel of 0.651×10^6 was obtained from the currently used heat-treated yield strength of 200,000 psi and the currently used yield factor of safety of 1.25 resulting in a proof hydrotest stress of 184,000 psi (density is 0.283). A 1961 index of 0.866×10^6 was obtained from an improved proof hydrotest stress of 245,000 psi associated with a 1.15 yield factor of safety and a 245,000 psi heat-treated yield strength. A 1964 index of 1.035×10^6 is obtained from an improved proof hydrotest stress of 293,000 psi associated with a 1.10 yield factor of safety and a 280,000 psi heat-treated yield strength. A 1966 index of 1.09×10^6 is hopefully anticipated with a slight improvement in proof hydrotest stress to 308,000 psi associated with the 1.10 yield factor of safety and a 295,000 psi heat-treated yield strength. These strength-index values are plotted in Fig. 9.

3.4.   Results

The question now arises: what have been the results of research and development aimed at meeting materials requirements set in 1960?

By 1965, the predictable development of the three chamber designs considered will lead to a situation where the strength-to-density ratios of all three materials, based on hoop stresses in cylindrical vessel bodies under ideal conditions, will be indistinguishable for all practical purposes (close to 1.1×10^6).

As shown by the actual strength index values plotted also in Fig. 9, our research and development, end-item oriented to a low-cost minimum-weight reliable glass-epoxy chamber, has led to 1964 properties slightly surpassing the projected goals. Actual values of proof hydrotest stress of 78,000 psi are being achieved in production of solid-propellant motor chambers today.

Development programs instituted in 1960 on filament-wound composites have covered (1) numerically controlled filament winding, (2) process variables such as winding tensions, (3) prepreg treatments, (4) resin investigations, (5) cure cycles, (6) mandrel designs, (7) optimum case design, (8) closure problems, (9) moisture pickup, (10) dimensional changes and tolerances, (11) and finally, the development of newer high strength glass, the Owens-Corning S-994, which demonstrates 30% improved strength properties over E-glass filaments. Based on these programs, the projected targets for 1965, estimated in 1960, can be more than adequately met.

The selection of the construction material for a specific motor case design must also take cognizance of other factors such as external loads, storage environment, aerodynamic heating, internal wall temperatures during combustion, reliability and costs. On cost alone, a choice in 1960 could have been made based on projected strength/density ratios being projected as near equivalent in 1965 production, with ratio of costs being roughly in the following order: Ti/glass ≈ 10/1 and steel glass ≈ 4.5/1, on a cost basis. These are only rough-order-of-magnitude estimates.

Development costs as well as production costs may likewise be expected to be greater for metal cases than glass cases; however, the reliability of glass cases may not be as high as desired because of the lack of understanding of a number of factors pertinent to composite structures:

*   Bond degradation -- shear strength loss on cyclic loading, heating (aerodynamic, etc.)

*   Effect of moisture absorbed during storage

*   Shear strength of the bonding resin in the presence of stresses due to external ground handling loads

*   The effect of resin curing process on the dimensions and shapes of the case and on residual stresses

*   Methods of flaw inspection for these composite structures

These questions have dictated the supporting research and development programs so that the glass filament-wound motor case could be tailor-made with end-service orientation in mind.

Perhaps, the greatest improvement in the state-of-the-art in the use of filament-wound structures for solid propellant motor chambers came about primarily from the interaction of materials research with design. The end goal, a minimum weight structure, could not have been obtained by research on materials alone, even with an all-out effort on the development of new glass compositions and newer resin systems. Instead, it resulted from the interaction of optimization in design and materials research, and with the analyses carried out to understand all of the pertinent factors of glass-chamber manufacture in order that the full properties of glass fibers could be obtained in the final end-item vessel. Since filaments carry load only along their axis (but not at any angle to their axis), minimum-weight glass chambers will be achieved when the industry is able to wind filaments exactly in the axis along which stresses are produced, thereby obtaining an isotensoid body. At burst pressure, all filaments are stressed to filament ultimate strength and all fail simultaneously. This condition has not yet been attained with closed-end vessels; it can be done with open-ended cylindrical bodies.

End domes have been the major stumbling block in attaining the reduced-weight potential of filament-wound glass chambers. Much research has been expended in the study of the end-dome contour. Because filaments on end domes cannot yet be placed to align exactly with developed stresses, more filaments than the required minimum are necessary. Since extra filaments on end domes become extra filaments longitudinally on the cylindrical portion of a chamber, full filament strength is not utilized in the longitudinally wound filaments. It was common, about a year ago, to have chambers in which hoop-wound filaments attained essentially 100% filament strength at burst while longitudinal filaments attained only 65% filament strength. Resin content of the composite did not have a very large effect.

When final modifications of end-dome contour were accomplished for optimum utilization of the glass fibers, strength utilization in all fibers more nearly approached 100% than any other design, permitting weight reductions.

4.   LIGHTWEIGHT, DUCTILE BERYLLIUM-ALUMINUM ALLOYS

Another example in which advanced requirements for aerospace missions have directed the development of new materials is the series of new beryllium-aluminum alloys, designated Lockalloy, developed by Lockheed Missiles & Space Company. In this case the requirements were not specific to one missile system but were general to a variety of potential vehicles (Ref. 8).

Theoretically, beryllium with its high Young's modulus of 42×10^6 psi and low density of 0.066 lb/in^3 is one of the best candidate materials for structural applications in missiles and spacecraft where compression buckling and crippling

is likely to be encountered. The serious drawbacks of pure beryllium are, of course, its brittleness and extreme sensitivity to surface damage. The results are poor fabricability and machinability. These serious objections have been largely overcome in the ductile Lockalloy, which retains much of the favorable elastic modulus and density of pure beryllium.

Lockalloys consist, essentially, of a fine beryllium network embedded in a matrix of ductile aluminum. The practical heat treatment and processing schedules give an extremely wide range of microstructures, and, consequently, a unusually large range of mechanical properties. Laboratory studies reveal that significant changes (5×10^6 psi) in Young's modulus can be obtained by heat treatment. These changes can be related quantitatively to the beryllium particle size and its complexity of shape. A further important discovery is that these alloys also manifest strain-aging behaviour.

Figures 10, 11, and 12 are comparisons of the elastic weight index versus composition for the Lockalloys and for other important competitive alloys. The elastic weight index, as used here, is the ratio of the density of the alloy to the square root of its modulus. The lower the value of the elastic weight index, the more suitable is the alloy. Beryllium has a value near 100, whereas aluminum and its alloys are near 300. The lockalloys, both in the rolled and annealed condition, have intermediate values around 140. The position of typical magnesium alloys is indicated by the squares along the right-hand side of the graph.

A comparison of the mechanical properties of Lockalloys is given in Fig. 13. The bar graphs depict the relative values of tensile strength, yield strength, bend angle, density, and elastic modulus for the Lockalloys, beryllium, magnesium, and aluminum. This method of presentation shows quite clearly the favorable overall properties of the Lockalloys.

This newly developed structural composite alloy offers: (1) significant weight savings over Mg and Al alloys in compressively loaded structure and (2) advantages over Be in the form of improved useful ductility; relative insensitivity to surface damage as compared to Be; freedom from tedious chemical etching after machining; and improved machinability, weldability, fabricability, and forming characteristics which should result in significantly lower installed cost. The range of modulus, strength, density, and ductility available in Be-Al alloys presents a wide variety of previously unattainable trade-offs to the spacecraft designer, thus enabling him to meet many advanced system requirements.

5.   IMPREGNATED REFRACTORY METAL ROCKET
     MOTOR NOZZLES

One of the most severe environments with which we must cope in the aero-
space industry is that posed by the very hot and corrosive gases of the rocket mo-
tor exhaust. Materials suitable for use as nozzles for directing the flow of these
gases must meet a unique combination of rigorous requirements including the fol-
lowing:

*   Extreme stability of the structure (i.e., virtually zero change
         of the critical dimensions due to high pressure and temperature
         applications)

*   High resistance to thermal shock during heating and cooling to
         prevent structural failure of the component during service

*   Fabricability, including machinability, on an economical pro-
         duction scale

*   Optimum reliability and reproducibility of relatively large sized
         components

When these stringent specifications were applied in the case of a recent
nozzle development program, the choice of materials became by necessity extre-
mely limited (Ref. 9). Tungsten and tungsten composite materials were believed
to have more potential for meeting requirements than other high temperature re-
sistant materials of appropriate physical and chemical properties. However, the
requirements could not be completely satisfied with the materials and processes
at that time available. A materials development design and process optimization
program had to be initiated to bring to the stage of commercial availability mate-
rials with the desired combination of properties for nozzles by the time other
parts of the complete system were ready.

With the application of infiltrated tungsten, the program became success-
ful. Billets weighing up to 200 pounds of pressed and sintered tungsten of less
than theoretical density (80%) are infiltrated with a metal of high thermal con-
ductivity and high vapor pressure, such as copper or silver. Although much higher
in cost, silver is preferred over copper because it best fits the infiltrant require-
ments of a low boiling point under the softening temperature of the tungsten, a sa-
tisfactory temperature span in the liquid state, a high heat content in the trans-
formation from a solid to a vapor, and complete lack of reaction or alloying with
the tungsten.

Nozzles made from silver-infiltrated tungsten have shown no erosion in
full-scale prototype firings with high-energy propellants. Some thermal cracking
of the outer diameter of the throat inserts has been observed, but the cracking has

not hampered nozzle performance. However, as a result of improvement in manufacture, thermal cracking has been reduced to an allowable minimum. It is believed that transpiration cooling of the infiltrant, resulting in film blocking in the boundary layer of the exhaust, accounts for the superior behavior of the infiltrated tungsten nozzle inserts.

To achieve optimum end-use performance of this composite, all of the manufacturing processing variables must be rigidly controlled and carefully optimized. Two of these variables were found to have significant bearing upon the ultimate properties. One of these is the tungsten powder particle size, which apparently influences the ultimate matrix density, permeability, tensile strength and tensile modulus of elasticity. The other is the infiltration temperature and infiltrant feeding technique which significantly influence the composite tensile strength, which must be about 33,000 psi at 1500°F, and the thermal conductivity, which must be high enough to minimize thermal stresses. Figure 14 compares tensile strength of infiltrated tungsten with the pressed and sintered tungsten matrix while Table 4 gives the mechanical and physical properties of infiltrated tungsten at various temperatures.

With the demands for longer range in future missiles, longer burning times, higher mass flow rates, higher temperatures, and consequently higher energy propelants will be required. Required will be lighter-weight constructions of nozzle components capable of withstanding the severe environment. The state-of-the-art of materials technology at this time is such that a major breakthrough in materials development for nozzles is required to produce components of low _chemical reactivity, high erosion and thermal stress resistance, and low weight for service to temperatures as high as 7000 to 8000°F.

6.   CONCLUSIONS

In the preceding four examples, we have examined instances of materials developed with specific properties or combinations of properties to meet the requirements of advanced missile and spacecraft requirements. Not only have requirements on properties steadily become more stringent but also the compression in development time has become more evident. As shown in Fig. 15 (Ref. 10), W. S. Pellini of the U. S. Naval Research Laboratory has expressed this convergence of system complexity (increasing) and development time (decreasing) very succinctly:

"In the old days of evolutionary growth in functional capabilities, we could rely on the input from the day-to-day problems of hardware development to sense the direction of R&D required to attain the next incremental step in functional capability. In effect, research mana-

Table 4

SUMMARY OF MECHANICAL* AND PHYSICAL PROPERTIES OF 20% VCL
SILVER-TUNGSTEN (Ref. 9)

Temperature (°F)	0.2% Offset Yield Strength (10³ psi)	Ultimate Tensile Strength (10³ psi)	Modulus Of Elasticity (10⁶ psi)	Elongation in 1.25 in. (%)	Reduction In Area (%)	Ultimate Shear Strength (10³ psi)	Thermal Expansion ΔL in./in.	Thermal Conductivity (Btu/hr/ft²/°F/in.)
75	–	74.0	39.1	0	0	43.7	–	1450
500	–	67.2	36.4	0	0	38.8	1.1	900
1000	44.7	48.6	38.0	9.3	11.3	30.3	2.7	750
1500	–	46.7	30.0	2.9	3.1	23.5	3.8	640
2000	23.8	35.2	23.5	4.8	8.0	17.9	4.7	580
2500	15.3	15.9	16.1	7.0	17.3	11.7	6.0	500
3000	10.4	11.7	10.8	7.3	10.8	6.8	7.6	500
3500	7.0	6.4	8.3	4.7	13.7	4.1	9.1	450
4000	5.8	6.2	5.6	5.9	12.7	3.2	10.3	410

*Mechanical properties determined at a strain rate of 0.05 in./in./min

gement could proceed by adaptation, i.e., by sensing future direction
from current experience. Today, we must project to jump increases
in functional capabilities that can be attained only by jumps in capabi-
lities of materials to perform more efficiently or to endure more
severe environmental conditions. Actually, the analytical problem is
complicated by a variety of possible jumps, each with a specific related
jump in materials capabilities..."

It must be the job of the materials researcher to perform the necessary
analysis of requirements and to effect the necessary synthesis of materials to
make these jumps not only possible but to a high probability of success, predictable.

Future progress in the aerospace field is critically dependent on the solution
of these crucial materials problems as they arise. Materials requirements for
lunar space missions may reasonably be expected to be more severe than for sa-
tellite applications; Venus and Mars probes will put yet more rigorous demands
on our ingenuity in supplying materials.

Traditionally, the point of view of the user of materials was to fit the design
or product to the properties of a material. This attitude has changed. The major
concern now is finding and applying a material or materials with the right com-
bination of properties to meet the design and service conditions. This attitude
is end-service oriented, and leads obviously and inevitably, to the tailor-making
of materials.

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ACKNOWLEDGEMENTS
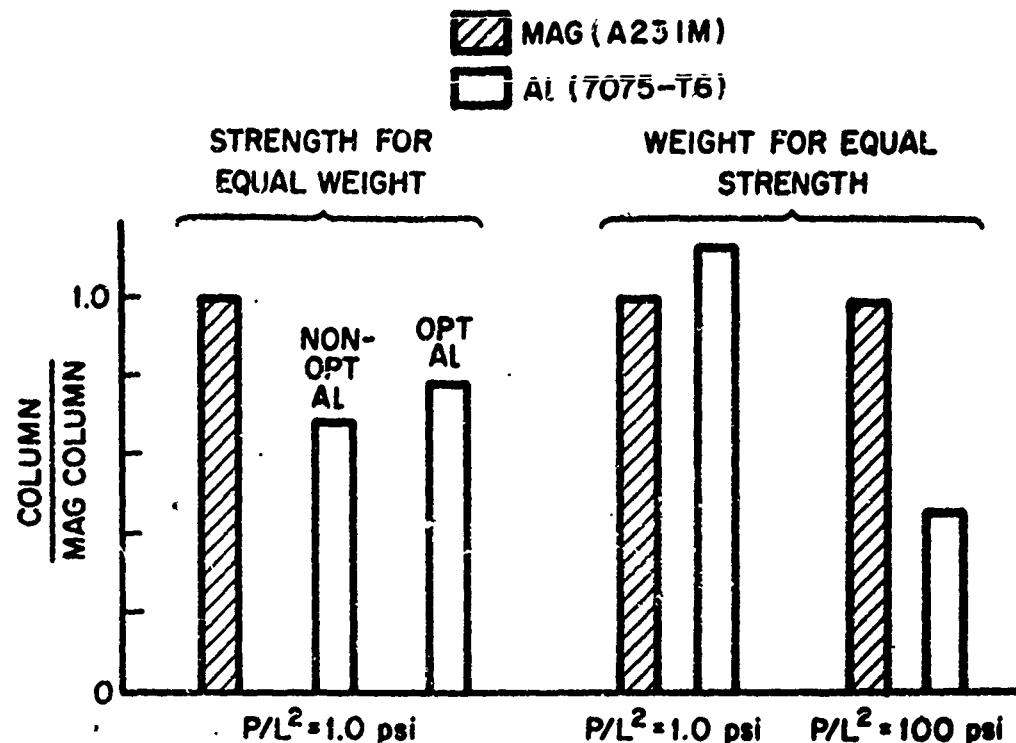
Fig. 1 Comparison of Relative Efficiency of Magnesium and Aluminum in Columns (Ref. 1)

TYPE	IRBM	ICBM	BOOST GLIDE (CIRCULAR)	SUPER-ORBITAL
V_{fps}	18,000	24,000	24,000 TO 26,000	36,000 (ESCAPE)
RANGE (NM)	1,800 TO 2,500	5,500 TO 7,500	1,000 TO 10,000	1,000 TO 10,000
$\dot{q}_{e+r_{max}}$	1,200	3,000	200 TO 500	200 TO 1,100
$\dot{Q}$	10,000	30,000	15,000 TO 20,000	50,000 TO 300,000
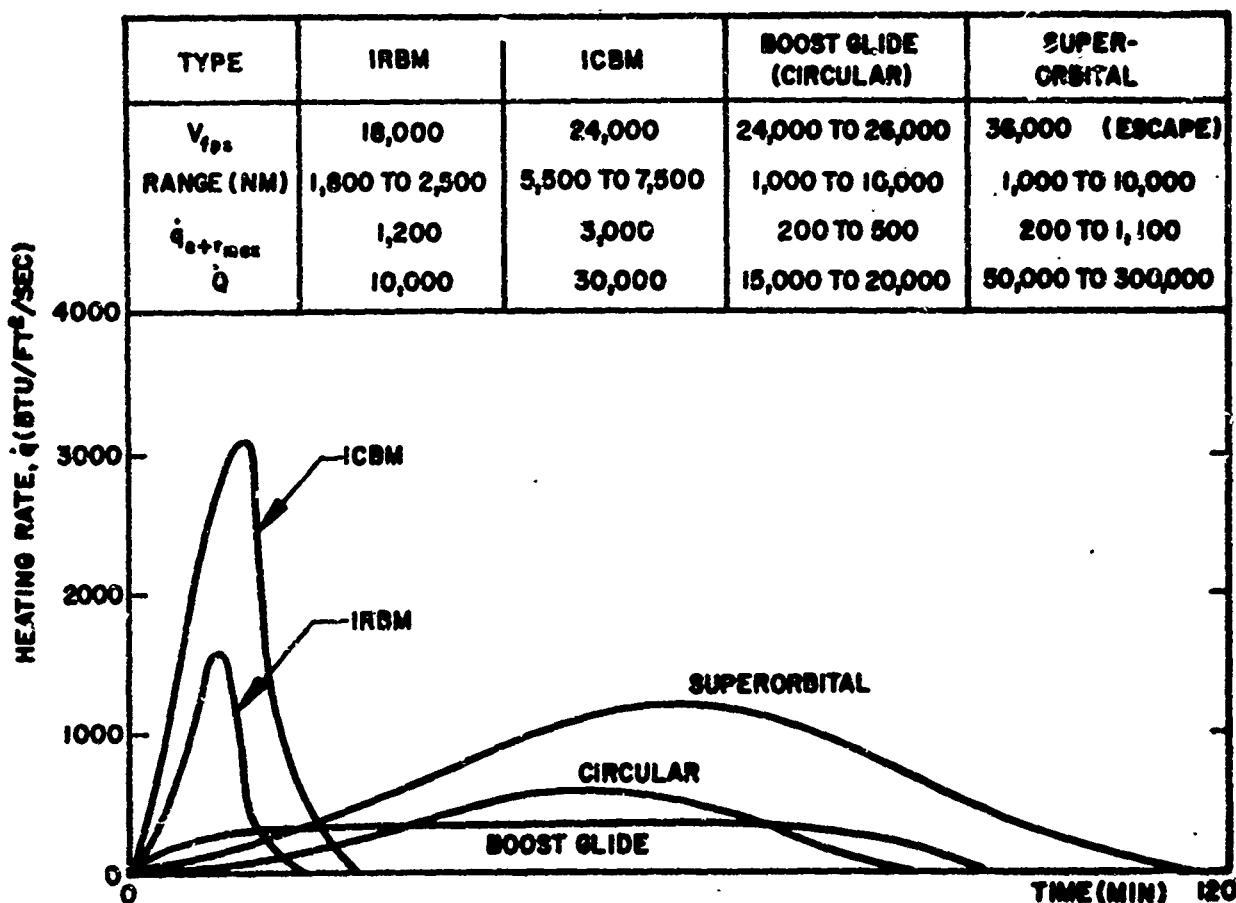
Figure 2   Comparison of Typical Reentry Parameters (Ref. 3)
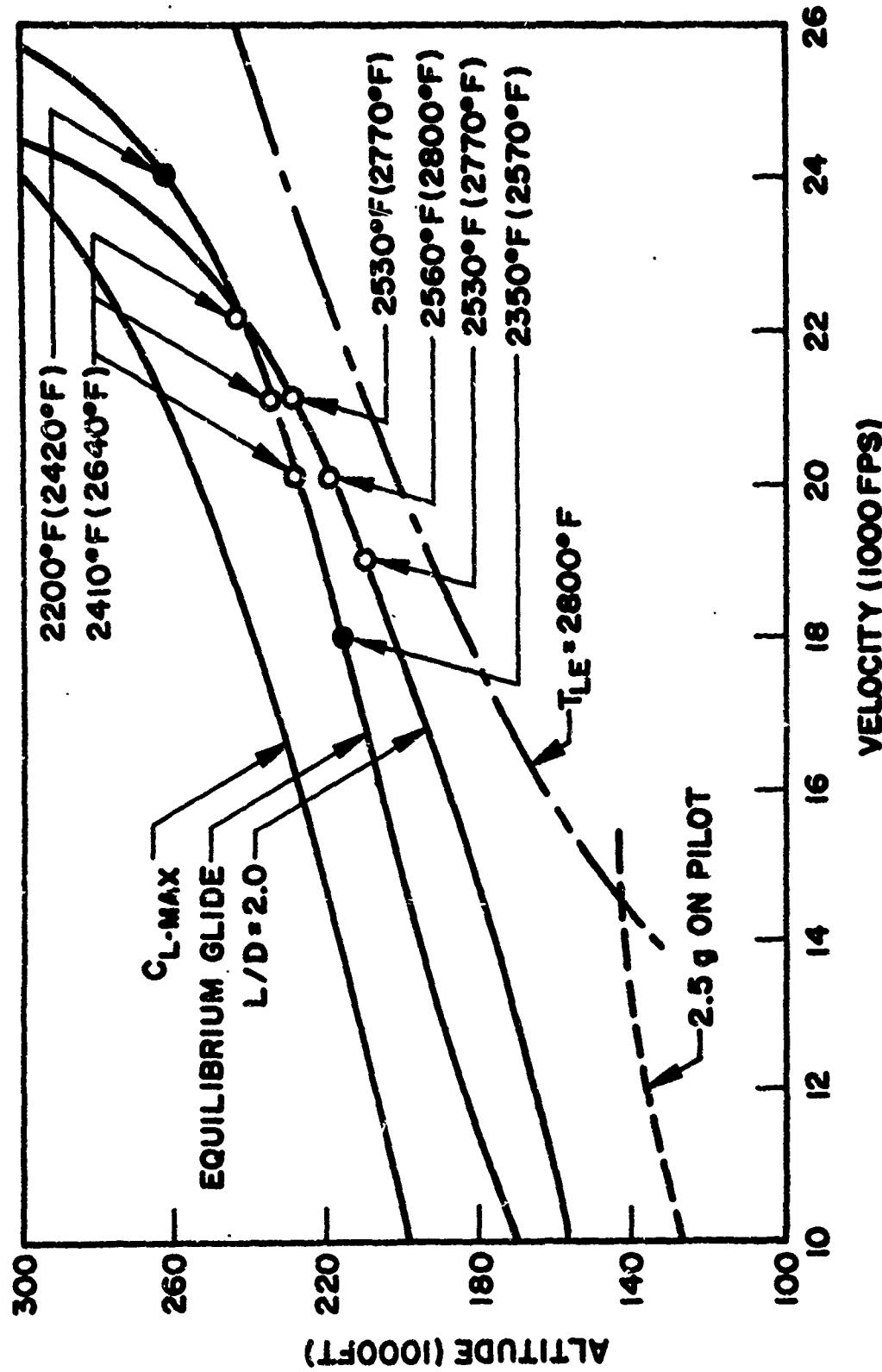
Fig. 3 Typical Flight Corridor of a Winged Reentry Vehicle $W/C_D A = 200$ lb/ft^2 (Ref. 4)
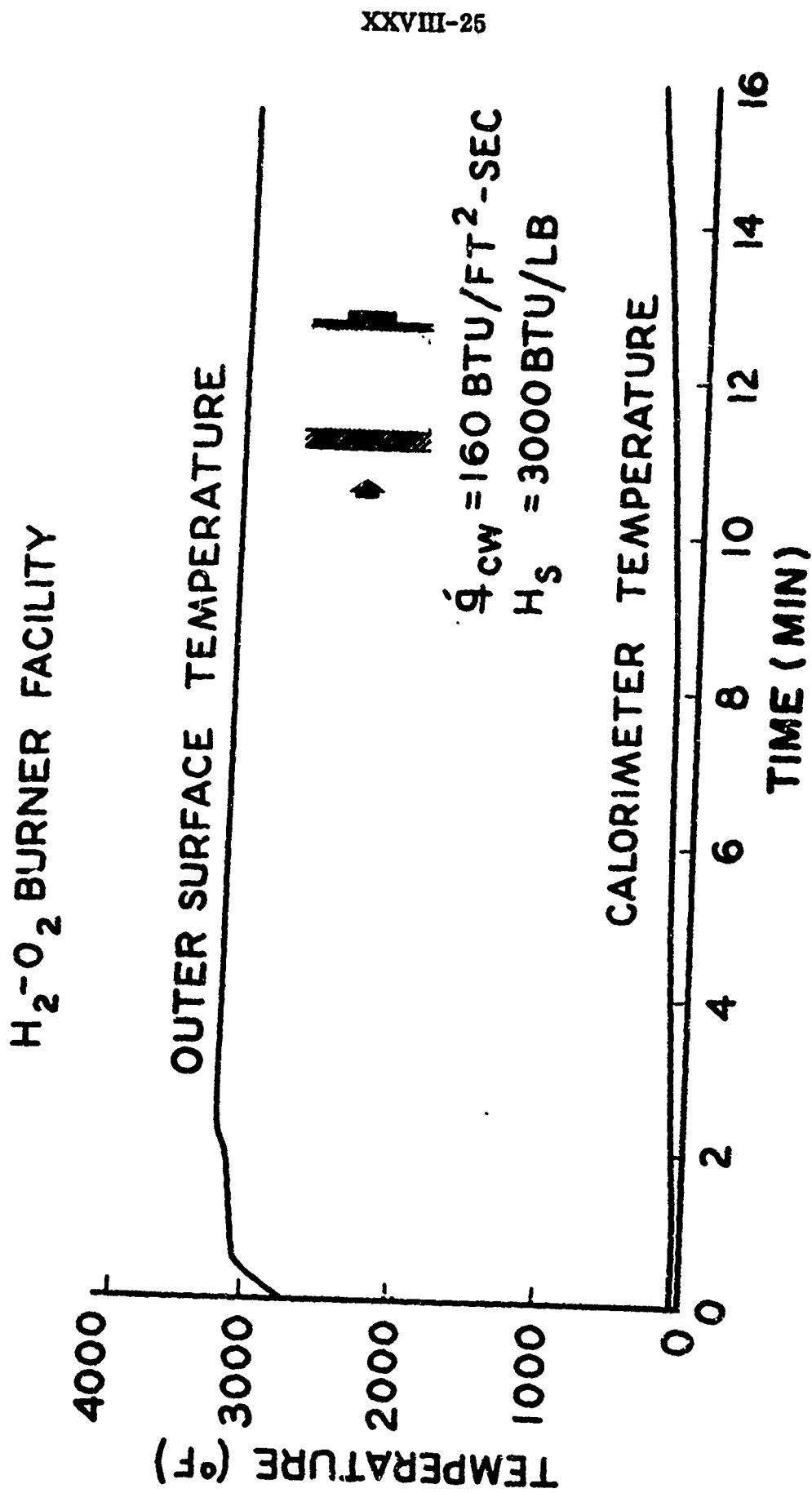
Fig. 4 . Temperature Response of Lock-Heat Composite
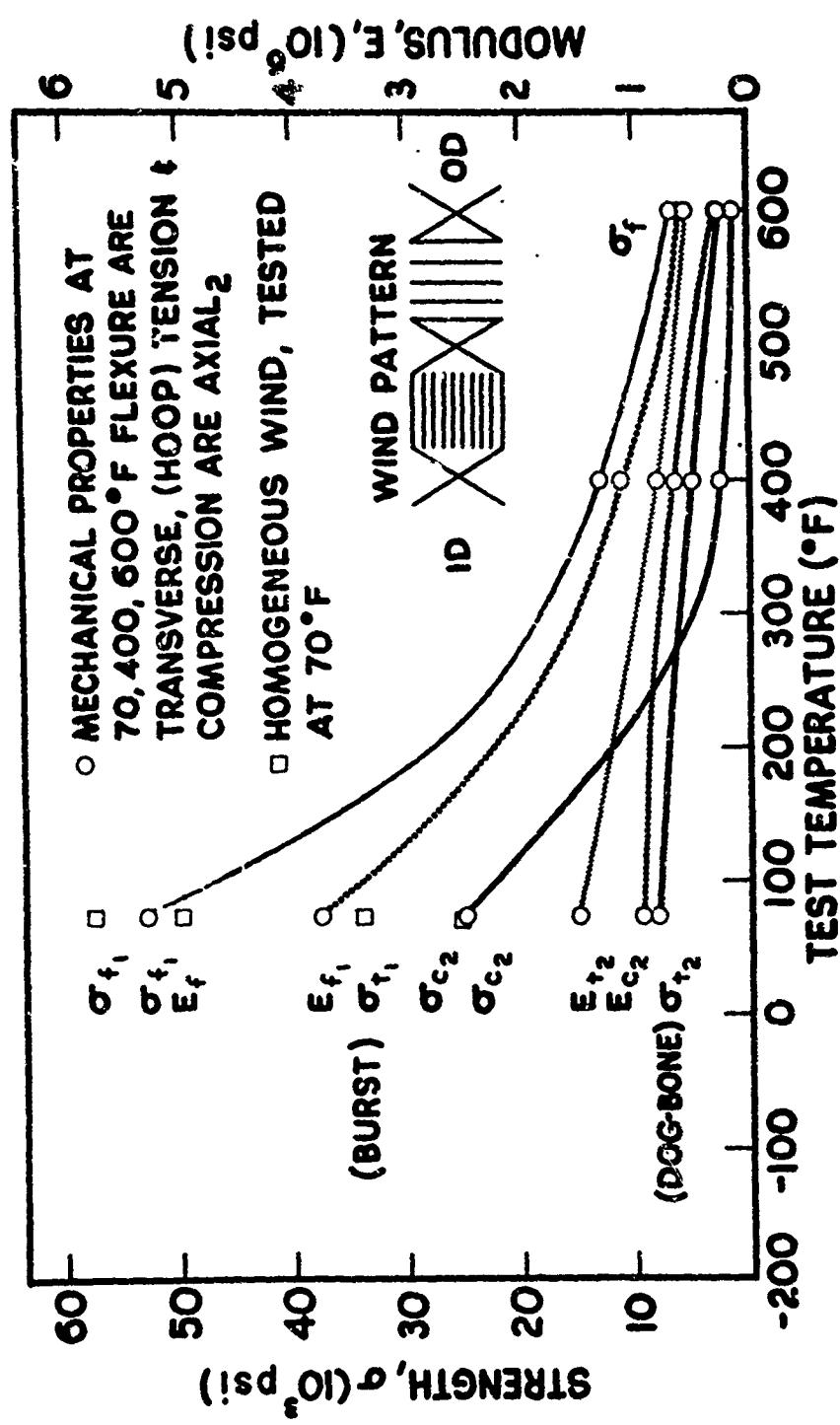
Fig. 5 Mechanical Properties of Lock-Heat
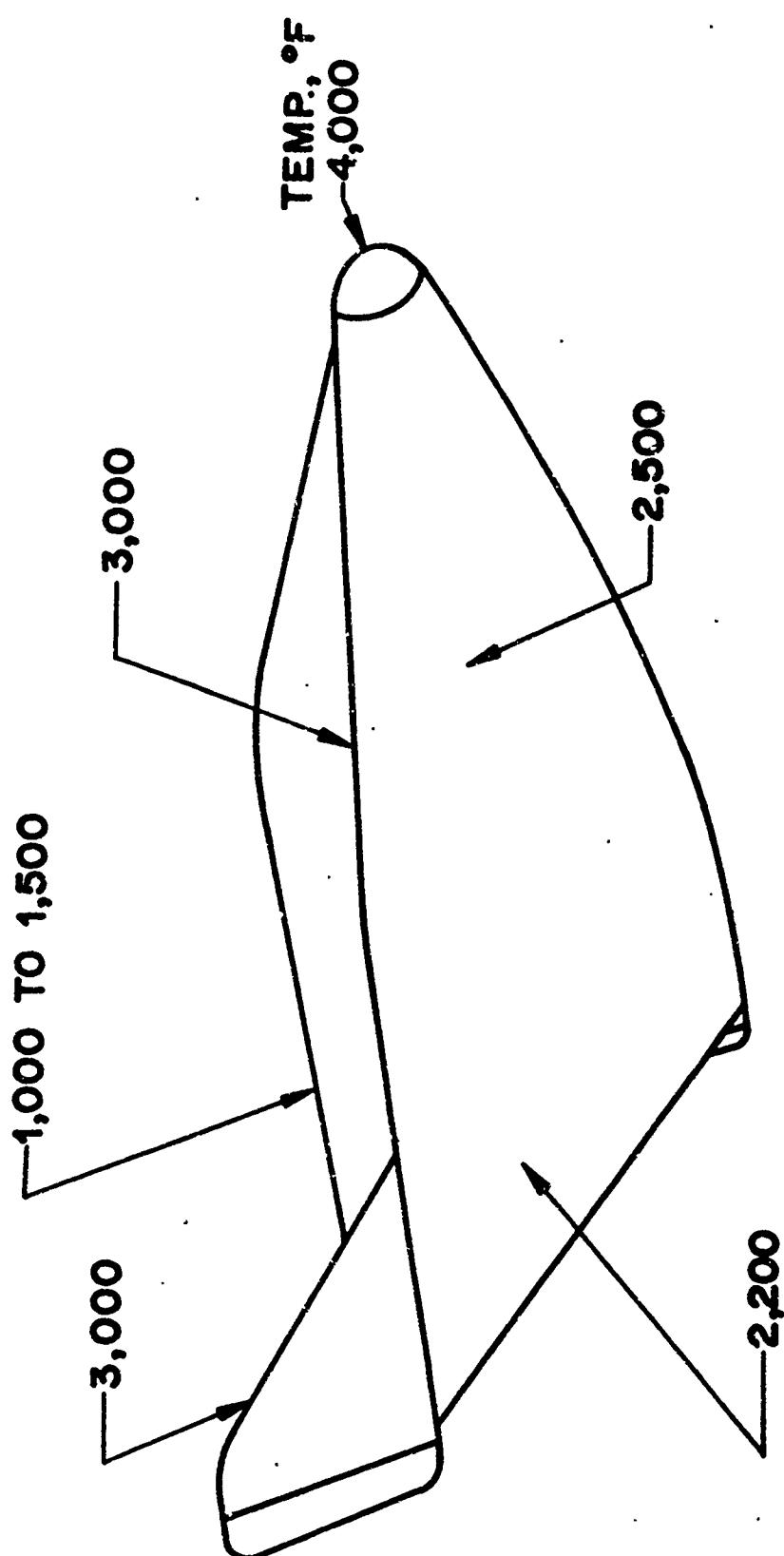
Fig. 6 Surface Radiation Equilibrium Temperatures for a Reentry Glider (Ref. 4)
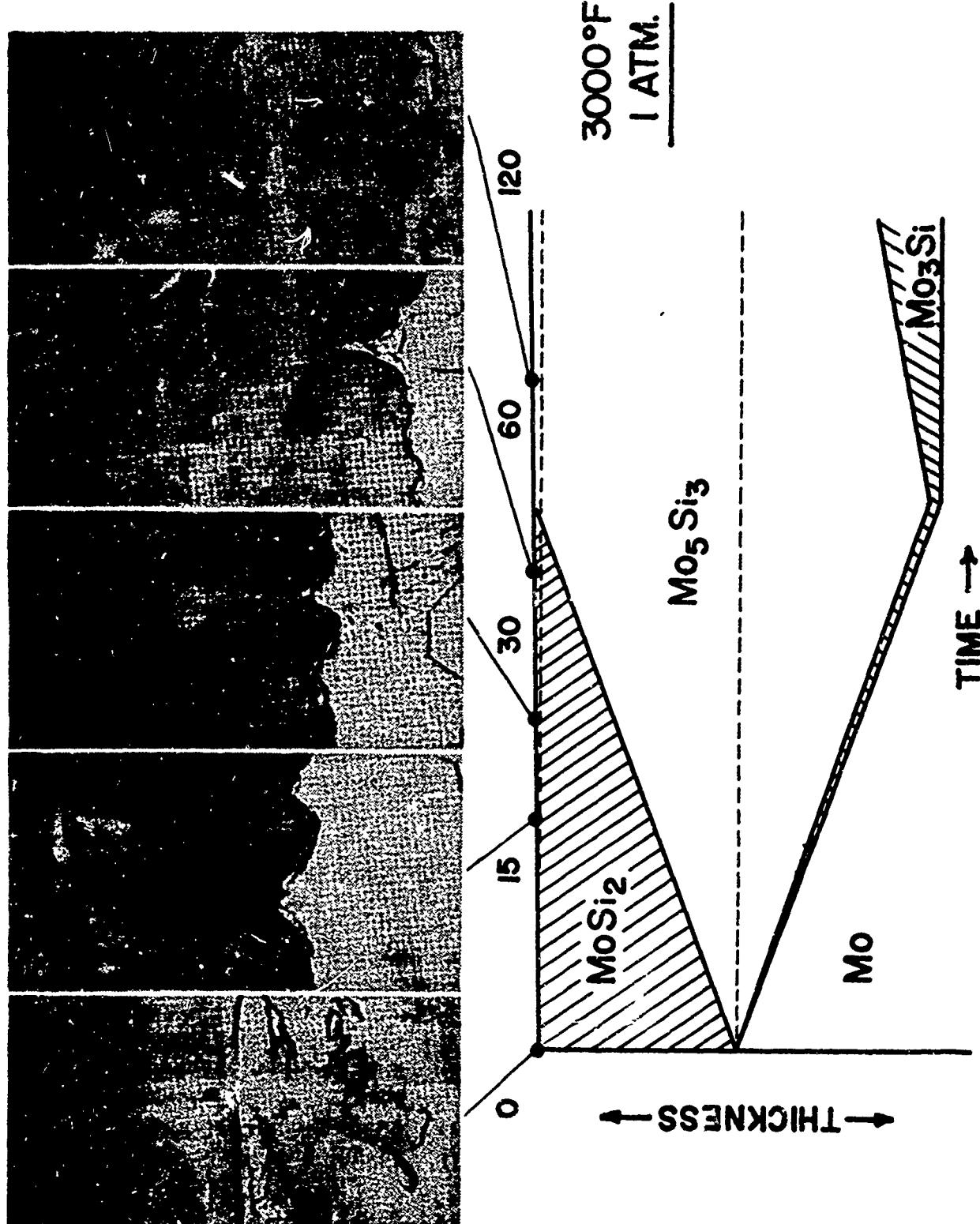
Fig. 7 Structural Changes Resulting From Diffusion of Silicon Into the Substrate (Ref. 6)

**AIR
1 ATMOSPHERE**

**STARTING THICKNESS
OF MoSi$_2$**

1-0.001 IN./SIDE
2-0.002 IN./SIDE
3-0.003 IN./SIDE

Fig. 8 Predicted Maximum Life of MoSi$_2$
Coatings on Mo as a Function
of Coating Thickness (Ref. 7)
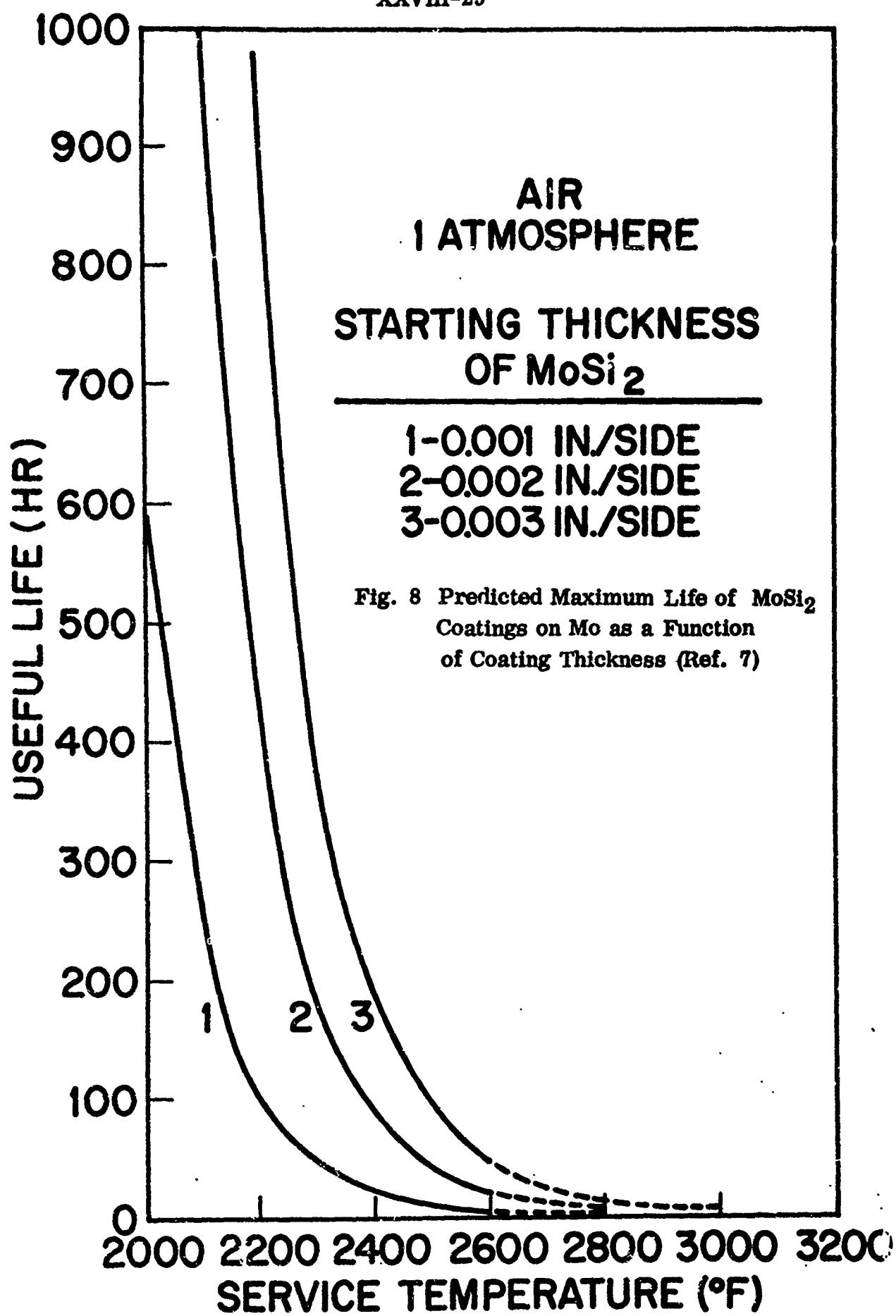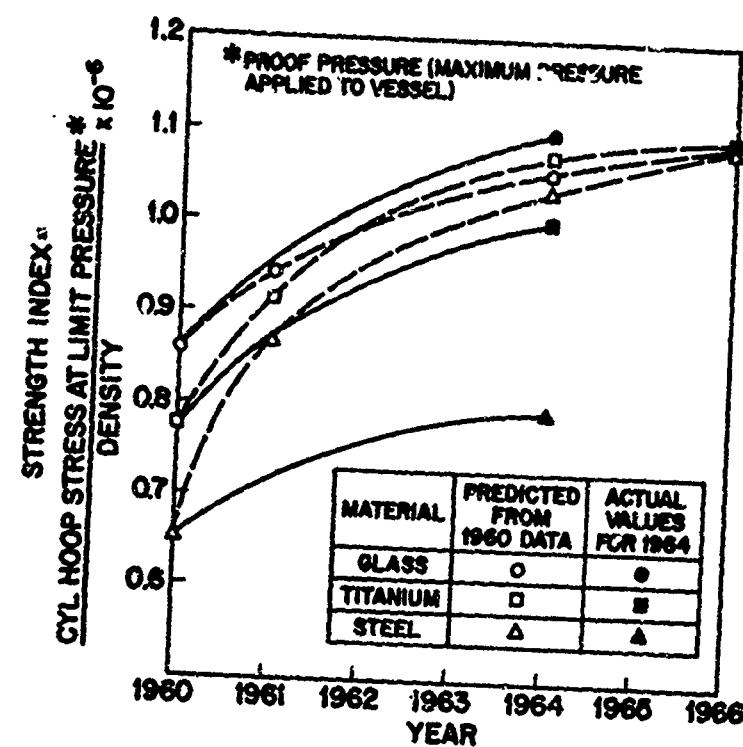
Fig. 9 Strength Index Values for Three
Structural Materials (Ref. 3)
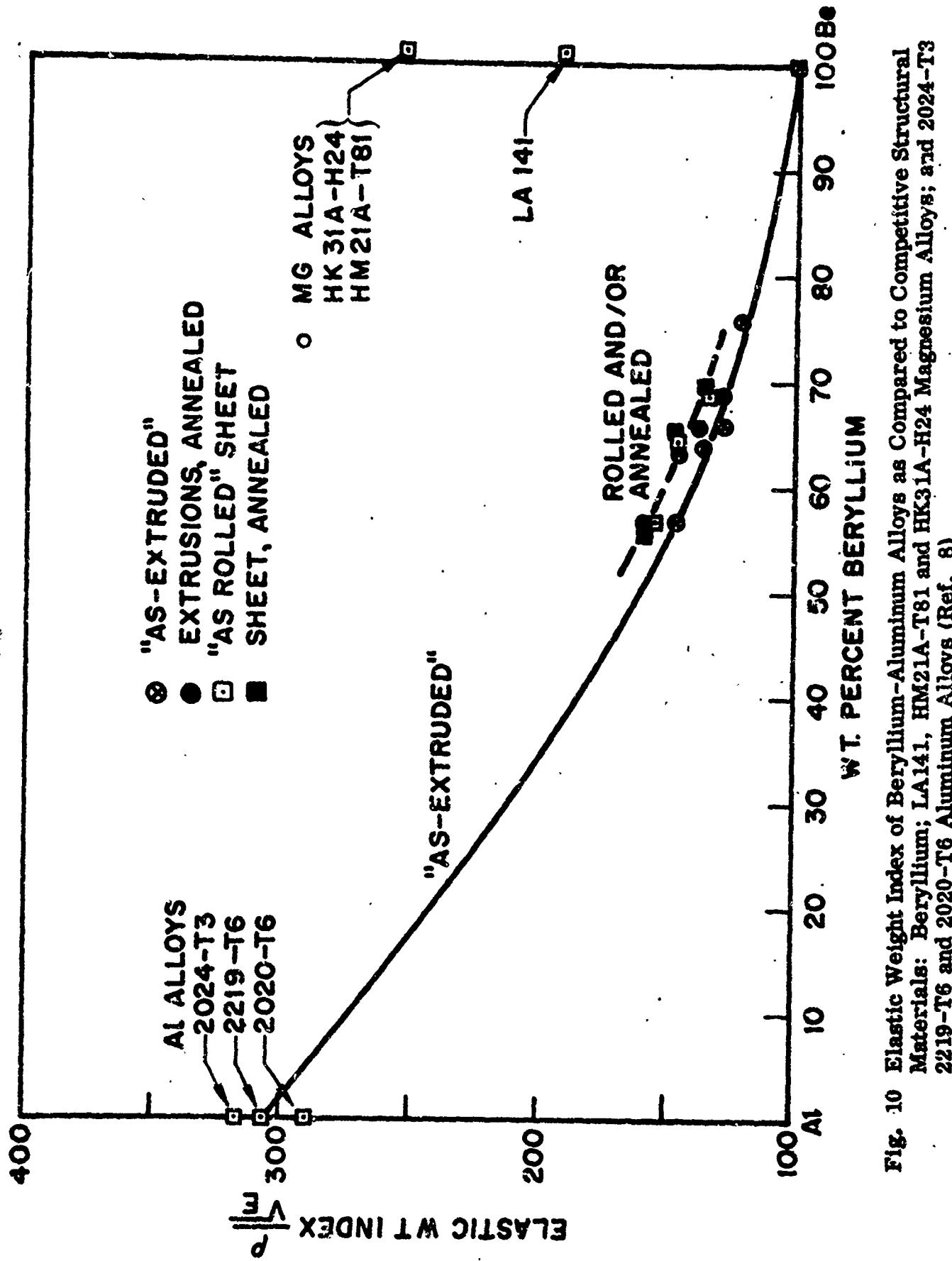
Fig. 10 Elastic Weight Index of Beryllium-Aluminum Alloys as Compared to Competitive Structural Materials: Beryllium; LA141, HM21A-T81 and HK31A-H24 Magnesium Alloys; and 2024-T3 2219-T6 and 2020-T6 Aluminum Alloys (Ref. 8)
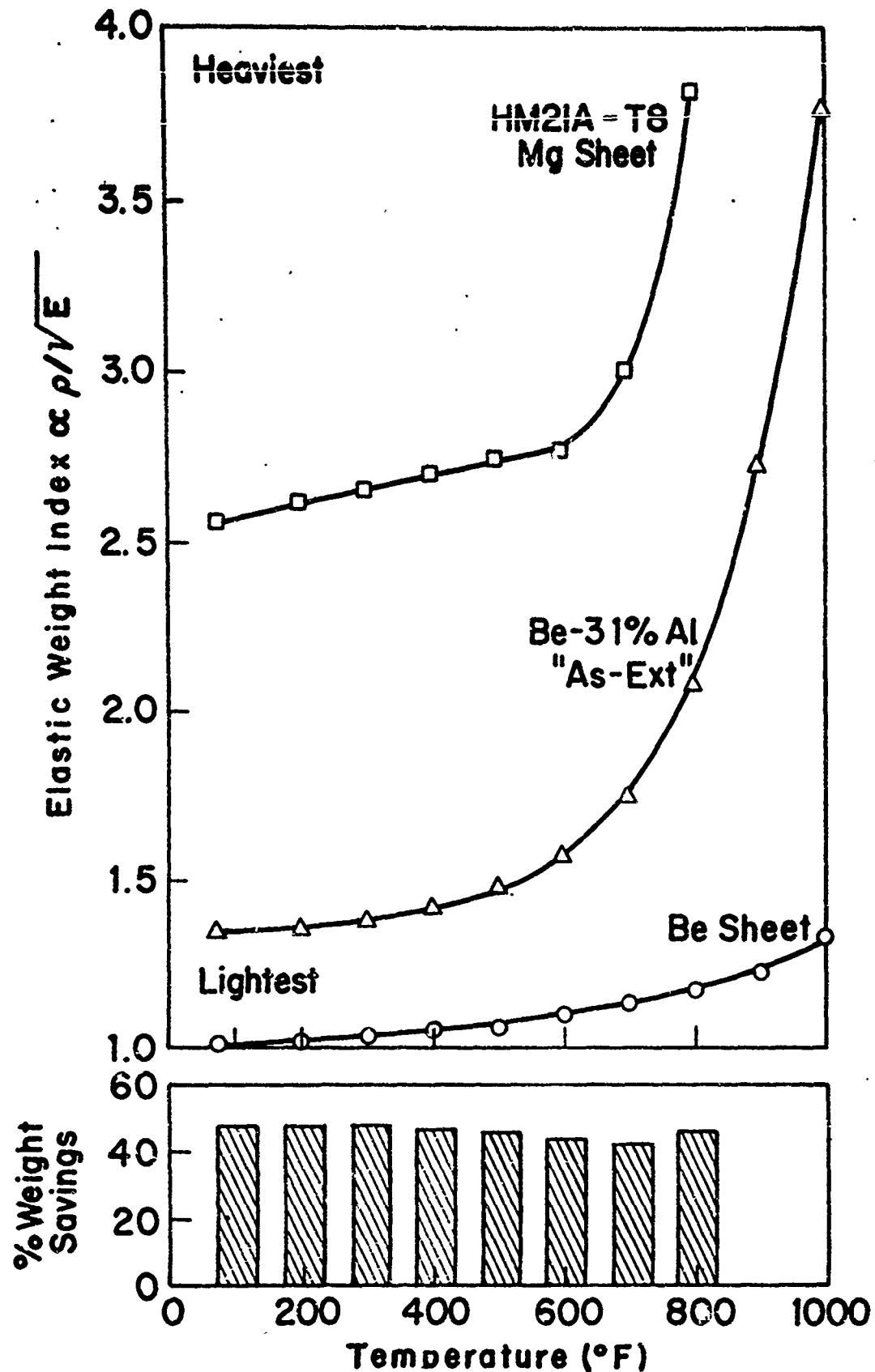
Fig. 11 (a) Elastic Weight Index of "As-Extruded" Be-31.4% Al Alloy Compared to Beryllium and HM21A-T8 Magnesium Sheet as a Function of Temperature; (b) Weight Saved by Substituting Be-31.4% Alloy for HM21A-T8 Magnesium Alloy as a Function of Temperature (Ref. 4)
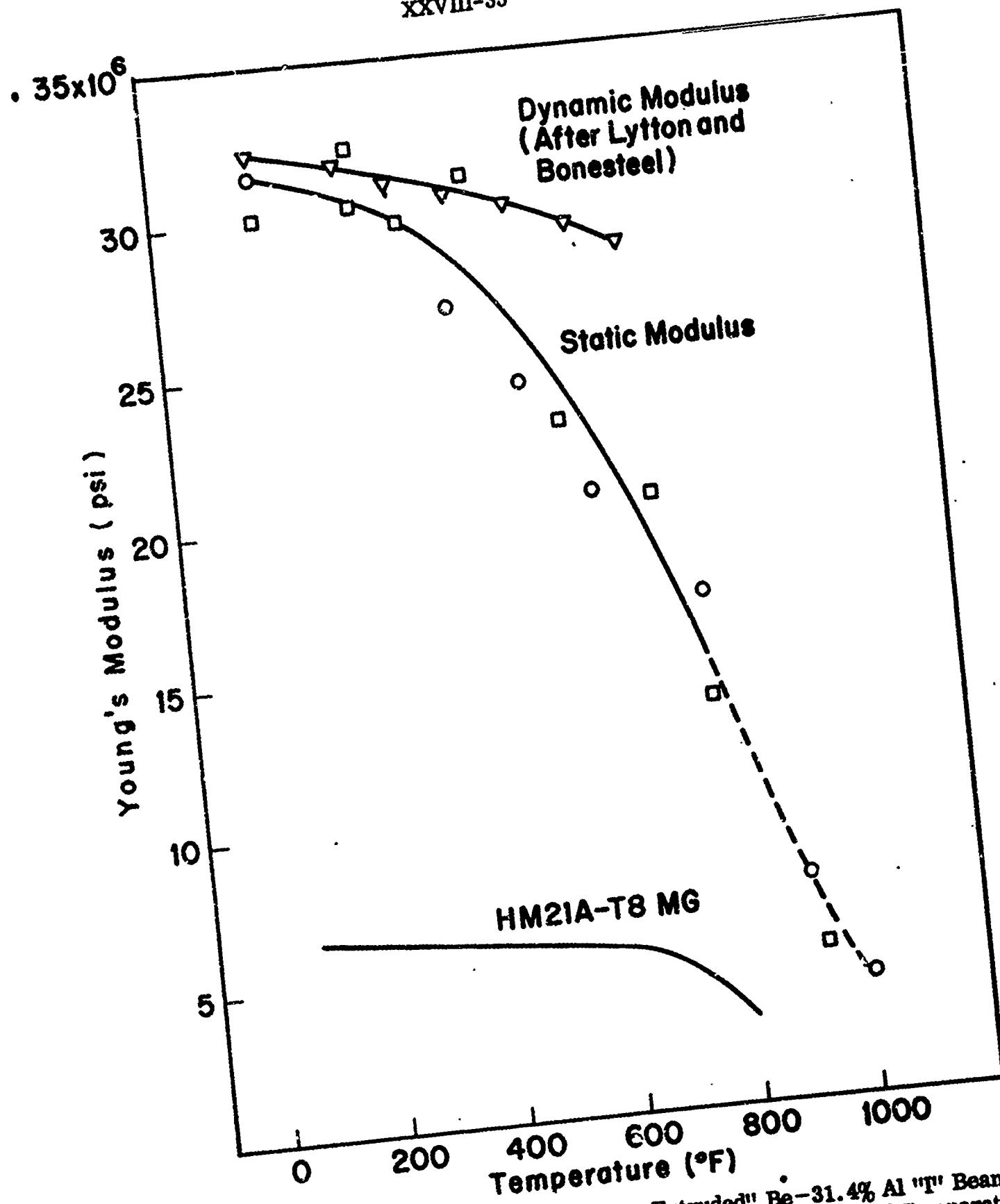
Fig. 12 Static and Dynamic Modulus of "As-Extruded" Be−31.4% Al "T" Beam Compared to HM21A-T8 Magnesium Alloy as a Function of Temperature (Longitudinal Direction) (Ref. 4)
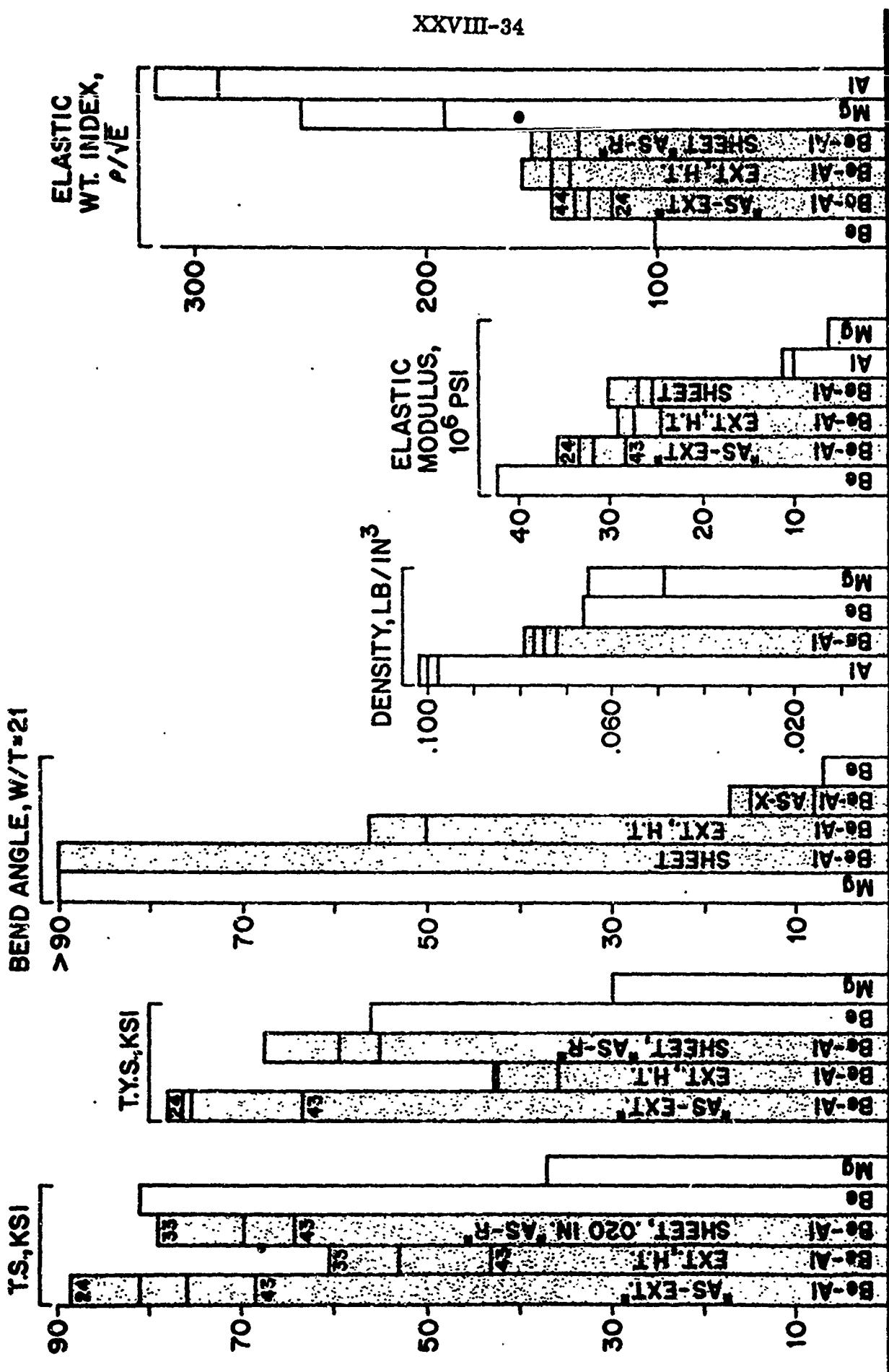
Fig. 13 Beryllium-Aluminum vs. Beryllium, Magnesium, and Aluminum at 75° F (Ref. 8)
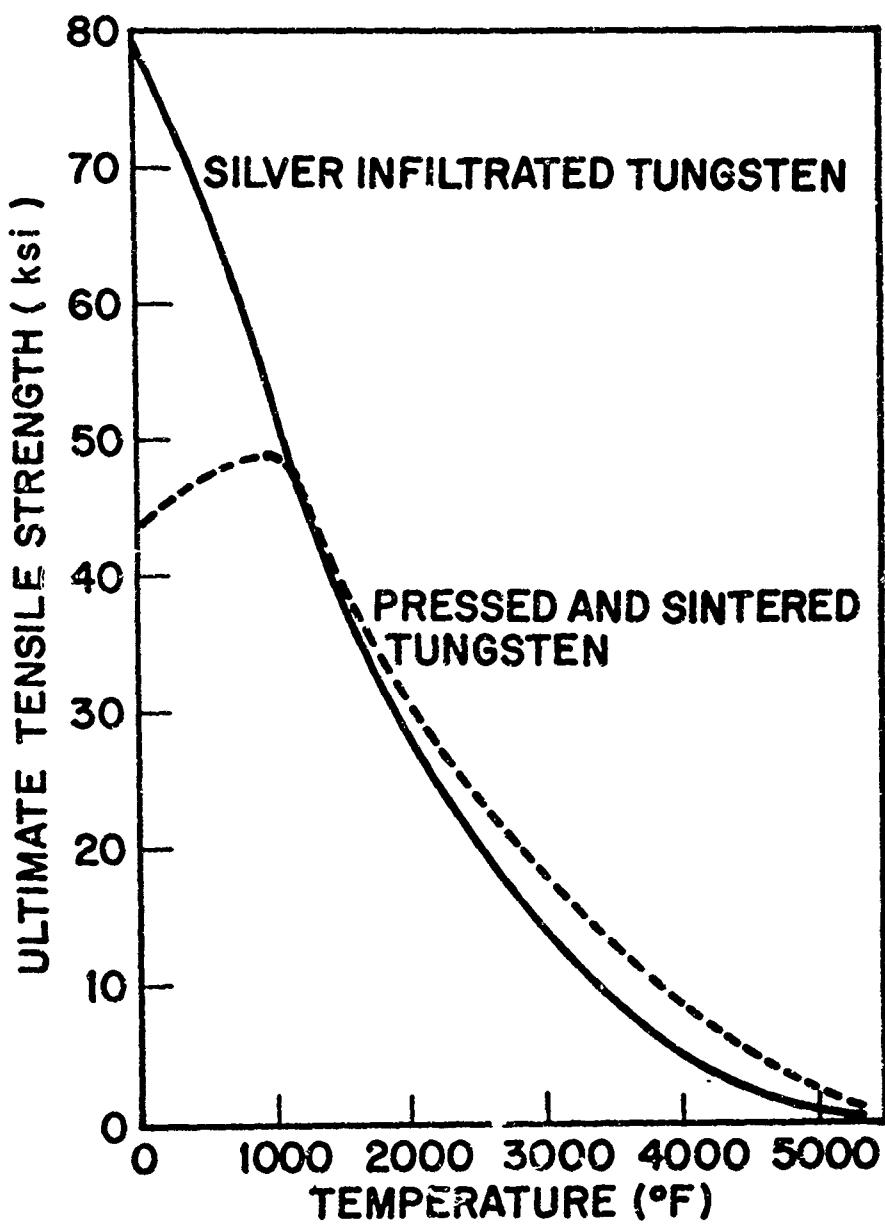
Fig. 14 Tensile Strength vs Temperature of Uninfiltrated
and Porous Tungsten Body (Ref. 9)
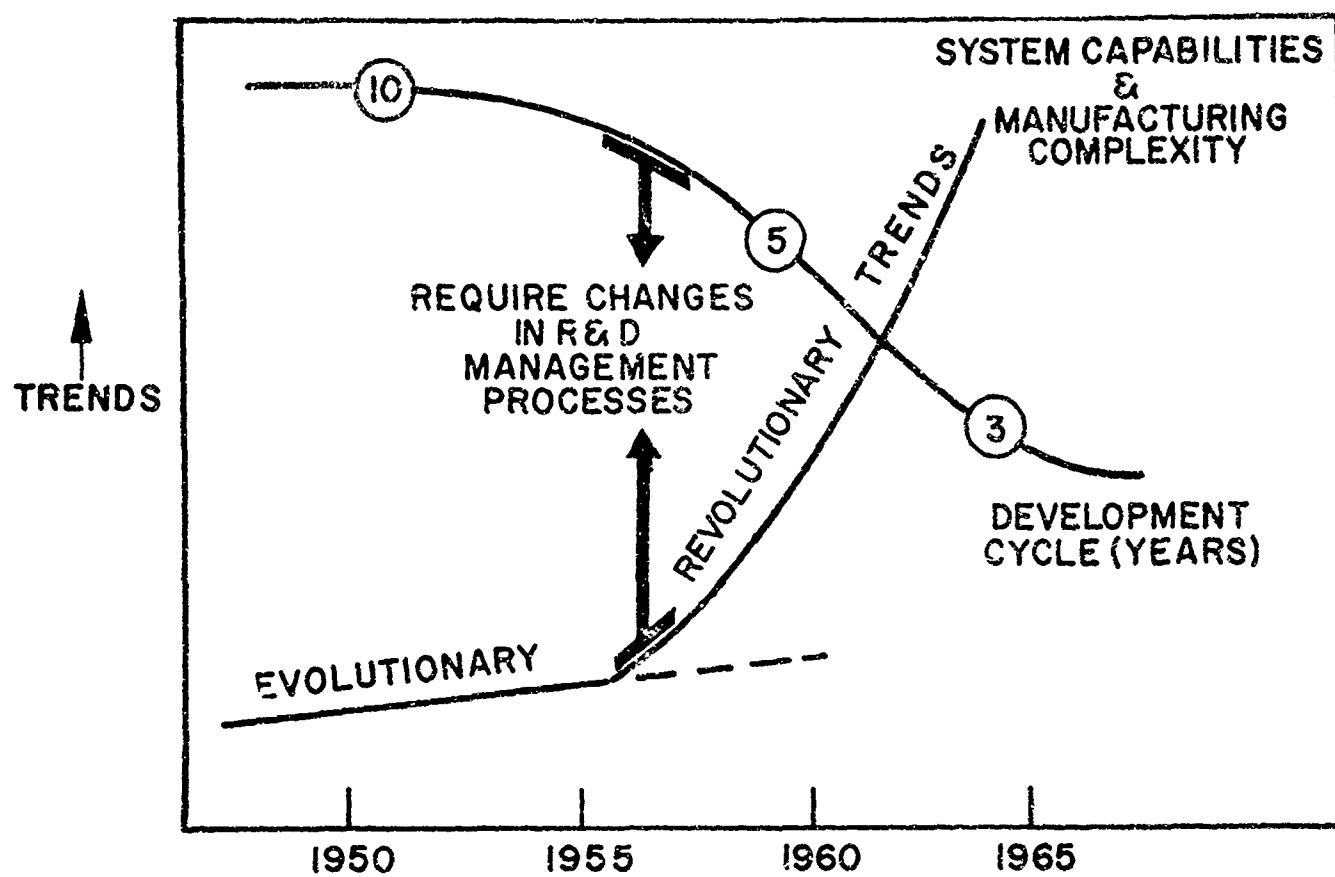
Fig. 15 Influence of System Factors on R & D Management Processes
(Ref. 10)

EXPLOSIVE WORKING OF METALS

by John S. Rinehart

Introduction

Many metals are now being worked using the forces generated by explosive charges, and within the past ten years, a whole new technology has developed in this area which has been adopted throughout the world by several hundred manufacturers. By now, the techniques for explosively working metals, compacting metal powders, work hardening, drawing, forming, swedging, welding, and cutting metals are well understood and established.

Utilization of explosives to do work is not new. Explosives have been used constructively for many centuries by mining and civil engineers and farmers for blasting rock and earth and for removing obstructions, and they have been used for destructive purposes in military operations. It is, therefore, somewhat surprising that metal workers delayed so long in adopting explosives as an effective tool. Perhaps the main reason for this is that a knowledge of explosives is not one of the normal accoutrements of the average engineer; in fact, most engineers consider explosives to be dangerous and uncontrollable materials, which, upon detonation, produce exceedingly unpredictable effects. Quite the contrary is the case. Explosives are only dangerous when misused. Their proper application is not hazardous, and their effects are just as predictable as other types of force generators commonly used in metal working operations.

EXPLOSIVES

Explosives fall into two categories: low explosives or propellants, and high explosives. Chemically the two types of explosives are not substantially different. They both contain chemical compounds rich in carbon, hydrogen, nitrogen, and oxygen, which react exothermically to produce large quantities of hot gases, carbon dioxide, carbon monoxide, nitrogen, and water vapor, that, on expansion, can work metals. The compositions of several explosives are listed in Table 1.

The heat of reaction ranges from about 700 cal/gm to 1200 cal/gm depending upon the explosive, and the amount of gas released is in the neighborhood of 1000 cc/gm when the gases have been expanded to normal temperature and pressure. Low explosives differ from high explosives in the rate at which the chemical reaction takes place. In low explosives, burning is relatively slow, only taking place at the surface of the material and moving inward at the rate of a few centimeters per second.

Furthermore, the rate of burning is strongly dependent upon ambient pressure; thus, confined propellant charges burn much more rapidly than when unconfined. The usual propellant charge takes several milliseconds to burn itself out.

High explosives, on the other hand, react extremely rapidly, detonation proceeding through the explosive at a rate of 6000 to 7000 km/sec, and the reaction is insensitive to ambient pressure. High explosive charges are consumed in a matter of microseconds.

The pressures generated by low explosives depend upon the extent to which the evolved gases are confined, pressures commonly ranging from 20 to 5 kilobars. High explosives generate pressures of 200 to 300 kilobars, the pressure being independent of the amount of explosive or confinement.

METAL-EXPLOSIVE SYSTEMS: LOW EXPLOSIVES

Many types of metal-explosive systems have been developed, some utilizing low explosives, and others high explosives. The low explosive system is usually a closed system in which the propellant is sealed within the workpiece, which, in turn, is surrounded by the die. The part to be formed expands and assumes the desired shape as a consequence of the steady, relatively slowly developing internal pressure resulting from the burning of the propellant. In practice, for ease of operation, the systems shown in Figs. 1 and 2 are quite common, the charge being contained in a shot-gun-like cartridge, which is easily ignited externally. In the bulging operation of Fig. 1, the hot gases fill the work-piece, pushing it into its new shape which is determined by the shape of the die. The situation in Fig. 2, a free forming operation, is different in that the final pressure is preselected so that the workpiece assumes the desired shape without the use of a constraining die.

A modification of the same sort of system is the operation illustrated in Fig. 3. In this case, the propellant gases actuate a piston which, in turn, pushes against hydraulic fluid contained within the tublar blank to be formed, the fluid bulging the blank to the shape of the closed die.

A spark-igniter guide, having two bulges, and formed from Type 310

stainless steel tubing, is shown in Fig. 4 along with a blank of the type from which it was formed. The blank was 5/8 inch O.D., 2 7/8 inches long, with a .0... inch thick wall, and was formed in a closed system using smokeless powder in the manner illustrated in Fig. 1. This is simply one of the many parts that can be formed this way. The closed system utilizing propellants is especially suitable for forming thin walled tubes used in manufacture of aircraft parts. Also, many companies are successfully sizing tubing by this method.

Low explosives which are usually in the form of gun powder are easy to package, handle, and ignite. They are also relatively noise free. Consequently they are finding extensive usage in small parts industries. They have the disadvantage of being useful only in closed systems which are difficult to fabricate and maintain and especially so when the parts to be worked are large.

METAL-EXPLOSIVE SYSTEMS: HIGH EXPLOSIVES

High explosives are utilized in two ways: in one, called a stand-off operation, the explosive charge is placed some distance from the work-piece, usually with water separating them; in the second, called a contact operation, the explosive is placed in intimate contact with the work-piece, or may be separated slightly from it by an intervening layer of solid material.

STAND-OFF OPERATIONS

A typical stand-off operation utilizing a concentrated point charge is illustrated in Fig. 5. The charge is placed in water some distance above the work-piece, which in this case consists of a flat plate held down at the edges. The work-piece is above a die, and when it is struck by the shock wave generated by detonation of the explosive, it is pushed down to conform to the shape of the die. On detonation, the high pressure explosion products push against the water, creating an intense, transient pressure pulse, or shock wave, which moves down through the water with a velocity of about 2 km/sec. The actual part made from this operation, a small fuel filter for a jet engine, is shown in Fig. 6. This part was fabricated from 20... stainless steel, 0.005 inches thick and about 2 inches in diameter. The explosive was a detonator containing about 20 grains of explosive and was positioned 2 inches from the work-piece.

The duration and intensity of such a water shock depends upon two factors: the size of the explosive charge, and the distance from the charge, being related

specifically by the two equations:

$$P_m = A \ (W^{1/3}/R) \ D$$

and

$$I = B \ W^{1/3} \ (W^{1/3}/R) \ F$$

where A, B, D, and F are constants given in Table 2 for three different explosives; P is the peak pressure; I is the impulse; W is the weight of the charge; and R is the distance from the charge at which the pressure and impulse are measured.

Nomographs relating peak pressure to charge weight and distance, and impulse to charge weight and distance are reproduced in Figs. 7 and 8 for TNT. Nomographs for other explosives will not differ substantially from these. Note that peak pressure and impulse are much more sensitive to distance than to charge weight. The pressure time profiles of shock waves generated in water by a one pound charge TNT are illustrated in Fig. 9 for four distances from the charge. The maximum pressures are in the neighborhood of one kilobar and the duration of the waves of the order of 150 microseconds. In some stand-off operations, air instead of water separates explosive and work-piece.

Since the coupling or impedance match between the explosive and air is so much less than the coupling between the explosive and water, the pressures of the shock waves in air will be very much less, one-fourth to one-fifth, than those in water, as illustrated in Fig. 10.

High explosives come in many forms, ranging from liquid nitroglycerin, which would never be used in an explosive forming operation, to granulated powders, cast and pressed blocks, and more convenient forms such as dynamite, sheet explosive, and Primacord. By far the easiest of these to use are the sheet explosive, an E. I. duPont de Nemours product consisting of a PETN-rubber mixture, and the Primacord, a small-diameter column of PETN wrapped in a plastic sheath, both of which can be readily cut and shaped. Electrically triggered detonators are generally available to set off the explosive.

A cubical, short cylindrical, or spherical charge produces a spherically expanding shock wave. In many explosive forming operations, such a shock does not produce the distribution of pressure on the work-piece that is best suited to forming the part, so that it is common practice to use other charge configurations.

The ring charge used in a cupping operation (Fig. 11) is made either from sheet explosive or Primacord. Such extended explosive charges are used when large pieces are being formed and it is desired to distribute the explosive force more evenly over a wider area. The arrangement of Fig. 11 has been used successfully in forming from 3/16 inch thick mild steel the 8 ft diameter railroad tank car head shown in Fig. 12. The ring charge consisted of 4.4. pounds of duPont EL 506 plastic sheet explosive.

The forming of a corrugated cylinder is best accomplished by using a line charge extending the full length along the axis of the cylinder as illustrated in the setup of Fig. 13. Figure 14 shows, on the left, a 6 inch diameter work-piece of 0.010 inch thick A-286 stainless steel, and, on the right, the final corrugated cylinder formed by this method. Tolerances in this case were 0.002 inches on the diameter. The explosive was a length of duPont mild detonating fuse.

The three systems, (concentrated point charge, Fig. 5; ring charge, Fig. 11; and line charge, Fig. 12), are only representative of a very large number of others which are essentially modifications, combinations, and permutations of these three. The sizes of the systems and the shapes and sizes of the parts produced therein range widely. The cupping operation of Fig. 11 has been used to produce parts weighing only a few ounces through missile noses 5 or 6 ft in diameter and on up to dishing the ends of tank cars and other structures many feet in diameter. There is almost no limit, small or large, to the size of piece. For exceedingly large pieces, multiple charges are sometimes used, these being fired either simultaneously or in sequence.

Techniques for choice of die construction, charge configuration, and detailed design features of many specific processes have been worked out. In most cases in the past, this has been done empirically using trial and error methods. However, a number of productive, more fundamental studies, are now underway. The matters to be considered are hold-down rings, die material, and die placement. A typical assembly for drawing a blank is illustrated in Fig. 15.

Hold-down is accomplished by a pressure plate held in place by 3/4 inch bolts. The space below the work-piece is sealed with and O-ring so that it can be evacuated. Evacuation is common in most operations of this type. The presence of air is not desirable for, on compression, when the work-piece begins to move, the air, being heated adiabatically, may cause the work-piece to weld itself to the die. The vacuum need not be a good one, a pressure of a few centimeters being entirely adequate.

There are many satisfactory die materials. Kirksite, the die material of Fig. 15, has been widely used because of its ease of fabrication. But equally satisfactory dies have been made from concrete alone, concrete lined with laminated plastics, wood, plaster of Paris, and other easily shaped materials, as well as steel and aluminum. The choice of a die material is determined by the nature and size of the part to be produced, and the number of parts. The entire die is then usually placed in a large tank of water where the explosive will be located.

The size and construction of the tank varies from operation to operation, but its construction presents no unusual problems. A typical tank is shown in Fig. 16. This has a somewhat special feature in that air bubbles are used to ameliorate the shock from the explosive, preventing the shock wave from damaging the tank itself. Such an air cushion, while a common feature of many tanks, is not at all essential if the tank itself is strong and large enough.

CONTACT OPERATIONS

Cutting, welding, and work hardening of metals, and the compaction of metal powders involve using explosive charges detonated in intimate contact with the materials being worked. Under such circumstances, the very high pressures, several million pounds per square inch, developed within the explosion products, act directly upon the metal, influencing it in a very different way than if a stand-off operation were used. On detonation, the explosion products push against the metal itself, setting up within it high intensity shock waves which traverse the metal at a rate of several thousand feet per second. The particle velocities associated with this shock are a few thousand feet per second, about 2,000 ft/sec in the case of an explosive detonated in contact with steel.

Consequently, during the transition of the shock, the material is highly compressed, to densities 30 to 40 percent above normal. Thus, the material, if a metal, may be substantially work hardened as a consequence of this compression. Manganese steel is especially amenable to work hardening in this way, and explosive hardening of manganese steel has been widely adopted in industry. The technique is to apply to the surface of the piece to be work hardened, commonly a railroad switch frog or the prongs of a steam shovel bucket, a layer of explosive in the form of duPont EL-506 sheet explosive, and then to detonate it. The increase of hardness achieved in this way is illustrated in Fig. 17.

If the material is a powder to be compacted, then the temporary density increase attained during transit of the shock wave is retained permanently as a result of the filling of voids in the material. A number of techniques have been adopted for accomplishing this compaction. Usually the full force of the explosion is too severe, breaking up the powder to be compacted, and must be attenuated. Water or steel or some other intermediary material is used to lessen the force of the explosion, as illustrated in Fig. 18. In this case, the powder to be compressed is placed within a steel tube which in turn is surrounded by a thin layer of explosive. On detonation, the explosive contracts the steel tube, which compresses against the powder, compacting it. Extremely high powder densities, greater than 99 percent, have been achieved in this way.

There are two types of cutting operations. In one, the full force of an explosive is used to shear the material in two, such as the cutting of an I-beam illustrated in Fig. 19. Such operations have been of great military import for many years, and consequently there exists a large amount of empirical data regarding the amount of explosive needed to accomplish various tasks. The second type of cutting operation is more subtle. The transient shock waves generated by the explosive charges are harnessed and directed to cut in a preselected manner. This has become more possible in recent years as the nature and interactions of such shock waves have become better understood. A typical example of the cutting action of such waves is illustrated in Fig. 20, which shows the way in which an explosive charge can be used to break up a square ingot into four large identical

pieces. Cutting results from the interference of reflected shock waves, tension waves arising from reflection at free surfaces of a compression wave.

There are a large number of situations like this in which stress waves can be used in a predictable manner to fracture cylinders, blocks, ingots, and like bodies. The guiding principle is that through the interference of transient stress waves, highly localized inhomogeneities in stress develop which break the material apart. Fracturing of this type is not always desirable, there being a number of cases in hardening or compacting materials using explosives where unwanted fracturing develops. Enough is now known about the dynamics of transient stresses and their various interactions so that usually such deleterious fracturing can be eliminated.

Welding or cladding of one metal by another has been one of the most successful of the contact explosive working operations. The two basic systems for accomplishing welding and cladding are illustrated in Figs. 21 and 22. In the system of Fig. 21, both plates are projected by explosive charges detonated simultaneously. In the operation of Fig. 22, the heavy plate to be cladded is placed on a firm foundation with the thin cladding plate projected against the parent plate by a single explosive charge. The stratagem is to project one plate against another at high velocity in such a way that a firm bond develops between the two. The critical parameter in the system is the angle β , the angle between the two plates.

CONCLUSIONS

Although it cannot be expected to replace most conventional metal working operations, explosive working of metals has now become firmly established in many metal processing plants. The processes where it has been most effectively and widely adopted fall into two categories: those in which the process can only be done by utilizing the exotic and extreme conditions generated by explosives, such as work hardening of manganese steel, compaction of metal powders, or the production of re-entrant contours; and second, those in which the working of the metal could be accomplished by other means but only at excessive expenditure of time, effort, and money. The sizing of missile noses, or the production of a railroad tank car fall into the second category. These operations could be performed by conventional methods, but construction and procurement of dies and presses required to produce these latter parts are only economically feasible when a large number of production parts are anticipated. Explosive forming of a few parts on the other hand is relatively inexpensive and simple since the dies and tanks required are relatively easy to fabricate.

While explosive working is playing an extremely significant role in the highly technologically developed countries such as the United States, it seems destined to

play an even more important role in less technologically advanced societies where progress is being hampered by the lack of expensive capital equipment. Since explosive forming, in most instances, requires relatively little capital outlay, the techniques are ideally suited to making up for this lack. There appears to be no reason why a country such as Argentina should not avail itself of these new explosive working methods and techniques to solve some of the metal working problems which it is now facing.

Table 1. Chemical Compositions of Several Explosives

Name	Formula
Nitroglycerin (NG)	$C_3H_5N_3O_9$
Nitrocellulose (NC.	$(C_6H_7H_3O_{11})\,n$
Trinitrotulene (TNT)	$C_7H_5\!\cdot_3O_6$
Pentaerythritol tetranitrate (PETN)	$C_5H_8N_{12}O_4$
Cyclotrimethylene trinitramine (CTMTN of RDX)	$C_3H_6N_6O_6$
Trinitrophenylmethylinitramine (Tetryl)	$C_7H_5O_8N_5$
Picric acid	$C_6H_3N_3O_7$
Lead trinitroresorcinate (lead styphnate)	$C_6H_3N_3O_9Pb$
Lead azide	PbN_6
Mercury fulminate	$C_2N_2O_2Hg$

Table 2. Parameters of Shock Wave Similarity Curves for Several Explosives

Explosive	Density	Peak Pressure P_m $10^{-4}A$	D	Impulse $I(t)$ B	F	Energy Density $E(t)$ $10^{-3}C$	G	Time of Integration
TNT	1.52	2.16	1.13	1.46	0.89	2.41	2.05	6.7 θ
Loose tetryl	0.93	2.14	1.15	1.73	0.98	3.00	2.10	5.0 θ
Pentolite	1.60	2.25	1.13	2.18	1.05	3.27	2.12	6.7 θ

(W in lb, R in ft, $E =$ in-lb/in^2, P_m in psi, I in lb- sec/in^2)
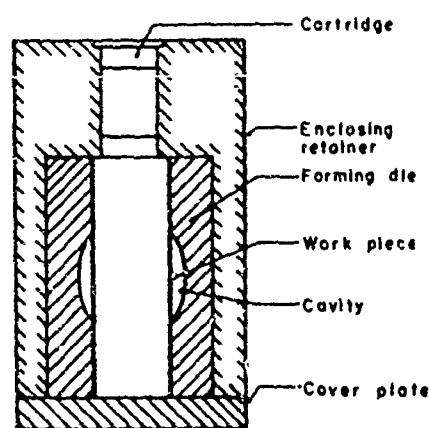
Figure 1   Bulging with a Powder Cartridge
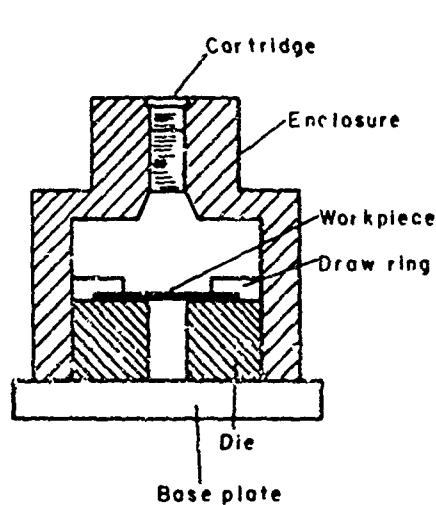
Figure 2   Free forming with
a Powder Cartridge
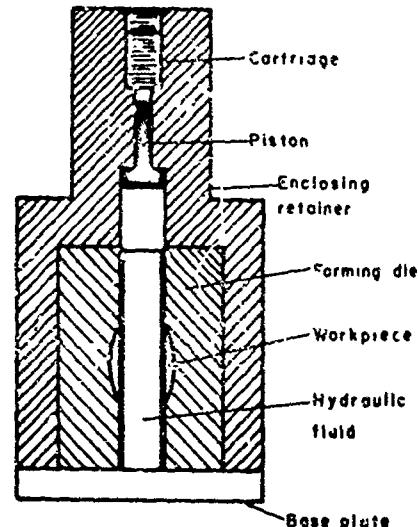
Figure 3   Bulging Operation with a
Cartirdge-Hydraulic System

Figure 4 Spark Igniter Guide and Preform (Courtesy Olin Mathieson Chemical Corp.)
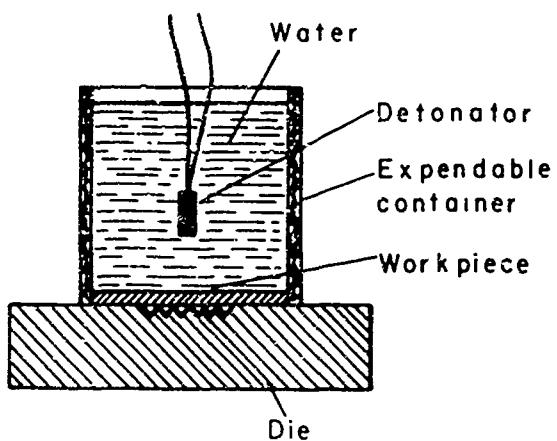
Figure 5 Method for Forming Flat Part with Detonator
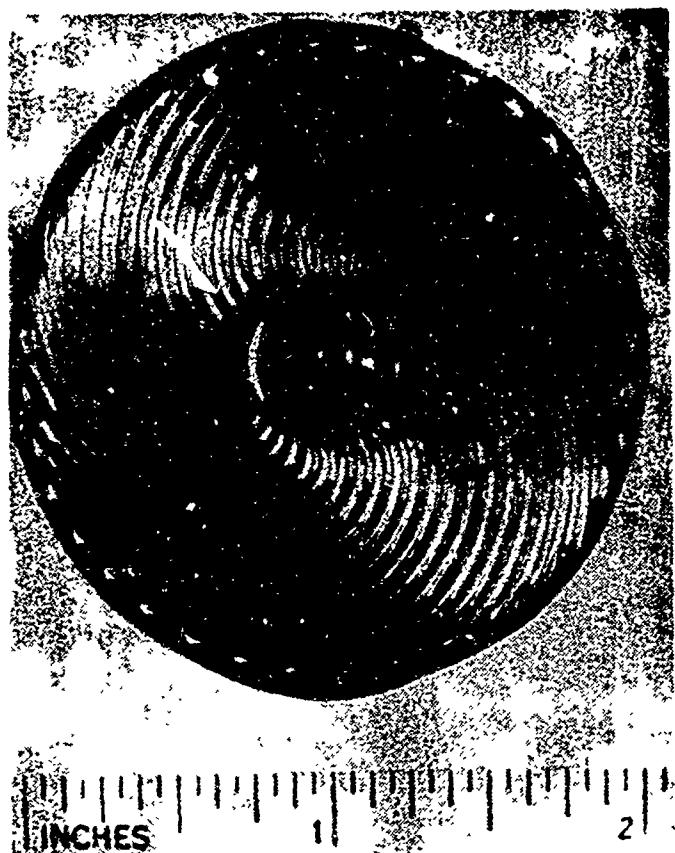
Figure 6   Jet Engine Fuel Filter

$$P_m = 2.16 \times 10^4 \left[\frac{W^{1/3}}{R}\right]^{1.13}$$

Explosive, TNT

W, lb

P_m, lb/in^2

R, ft.
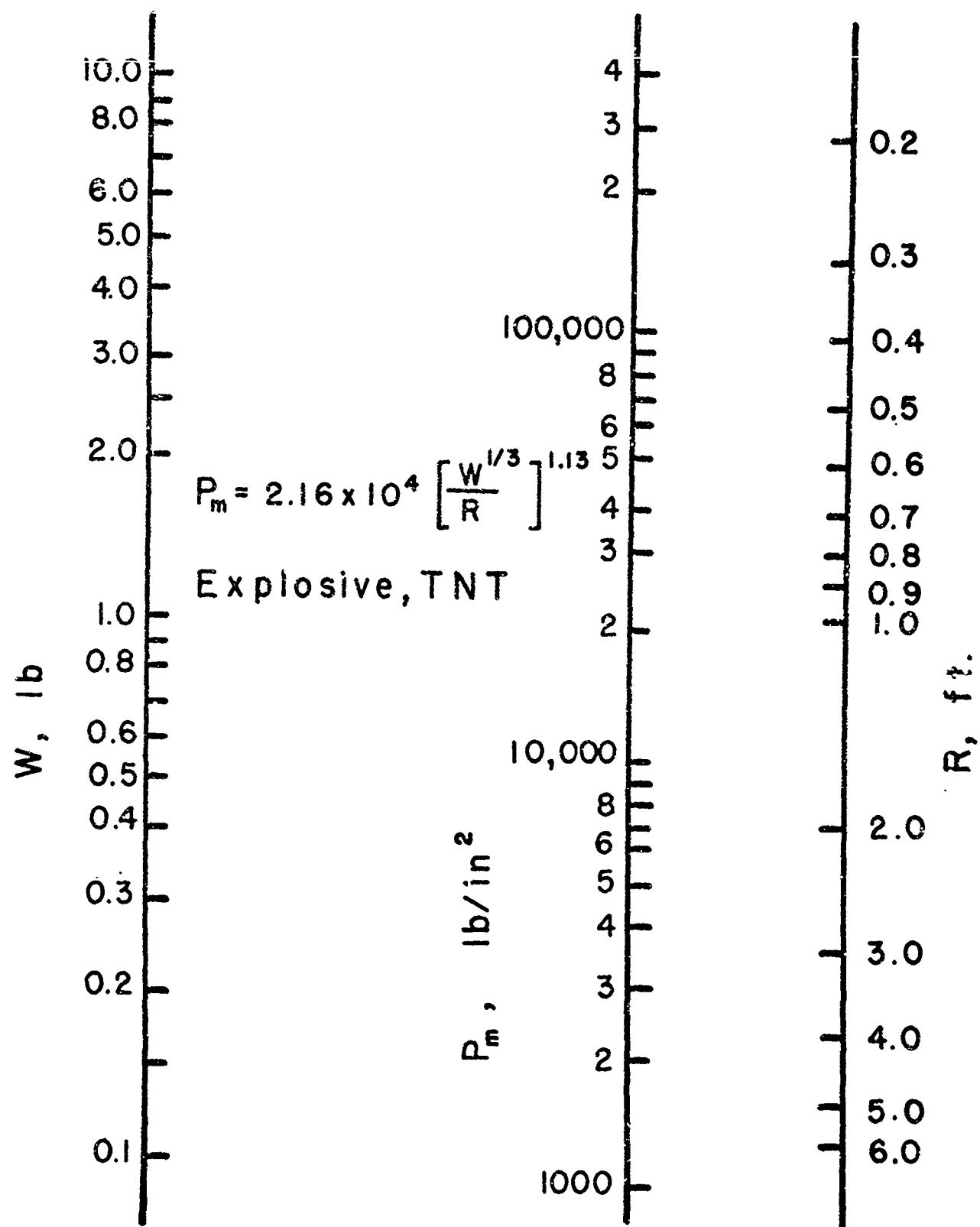
Figure 7   Nomograph for Computation of Pressures
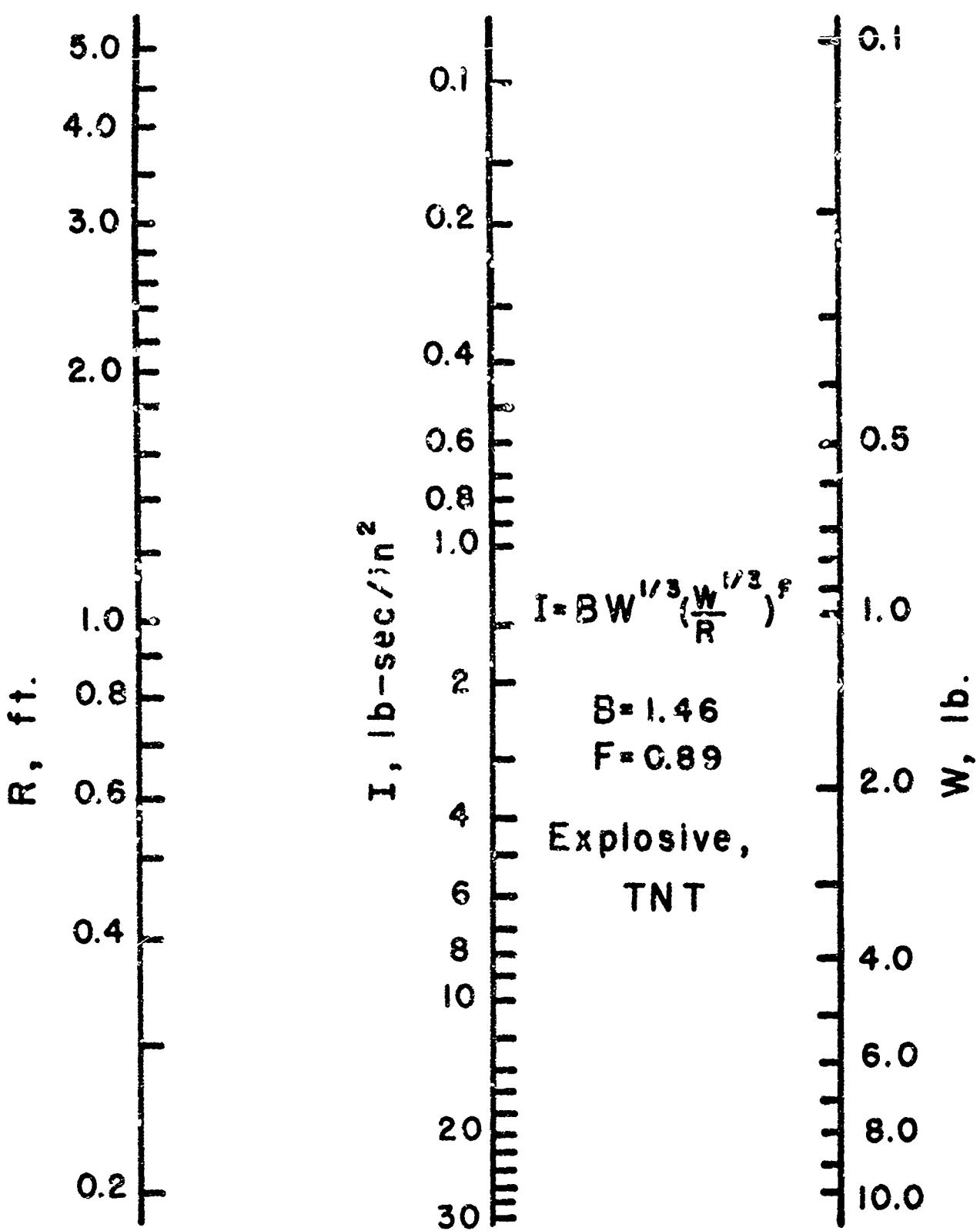
Figure 8   Nomograph for Computation of Impulses
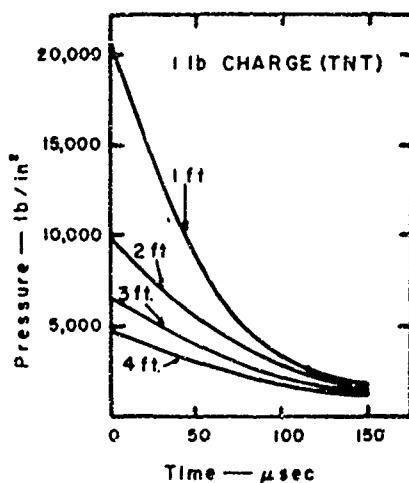
Figure 9 Pressure-Time Profiles of Shock Waves Explosively
Generated in Water
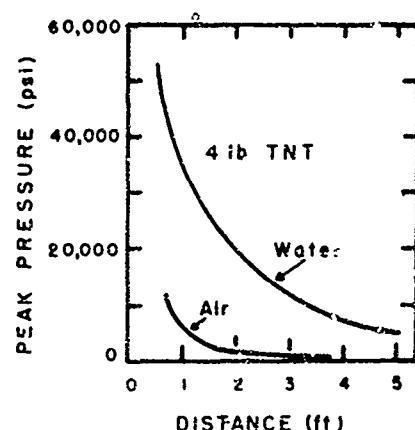
Figure 10 Comparison of Pressures in Shock Waves Generated
in Air and Water by Detonation of an Explosive Charge
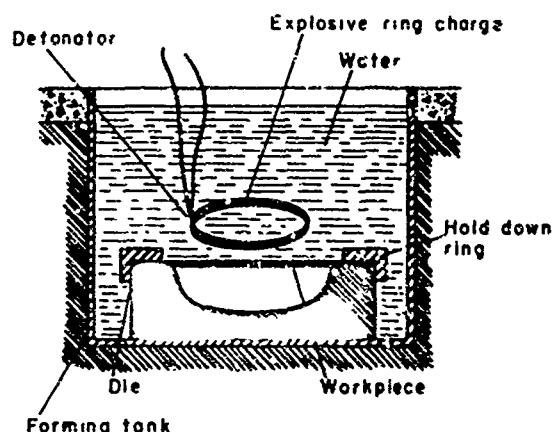
Figure 11 Method for Forming With a Ring-Shaped Charge

Figure 12   Tank Car Head (Courtesy E. I. duPont de Nemours, Inc.)
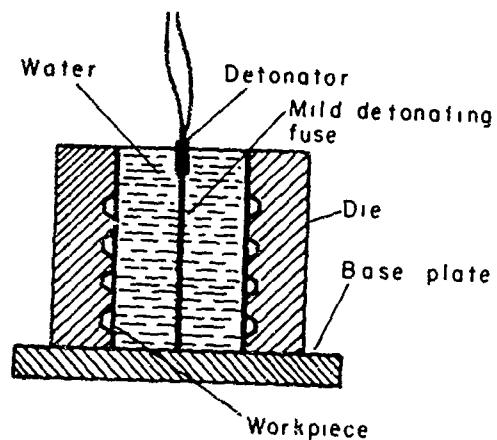
Figure 13   Method for Forming Corrugated Cylinder
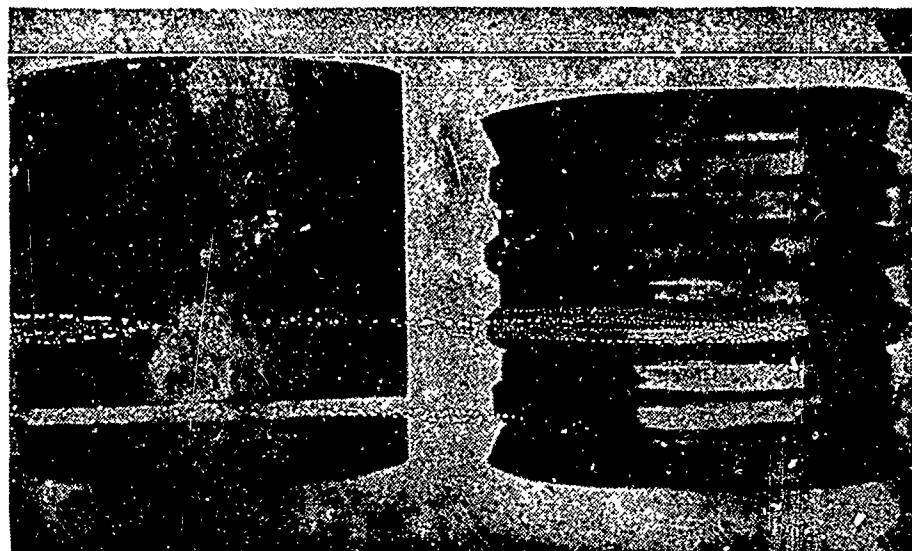
Figure 14   Formed Corrugated Cylinder (Courtesy E.I. duPont
de Nemours, Inc.)
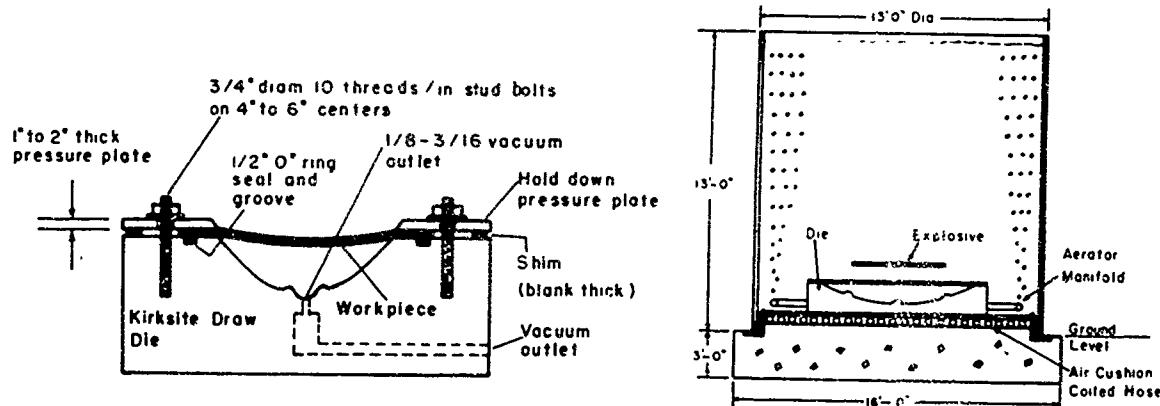
Figure 15 Typical Arrangement for
Drawing a Blank

Figure 16 Forming Tank
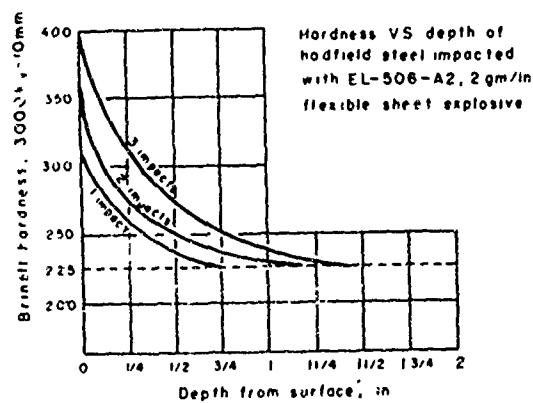
Figure 17   Hardness-Depth Curves for Explosively Hardening
Manganese Steel
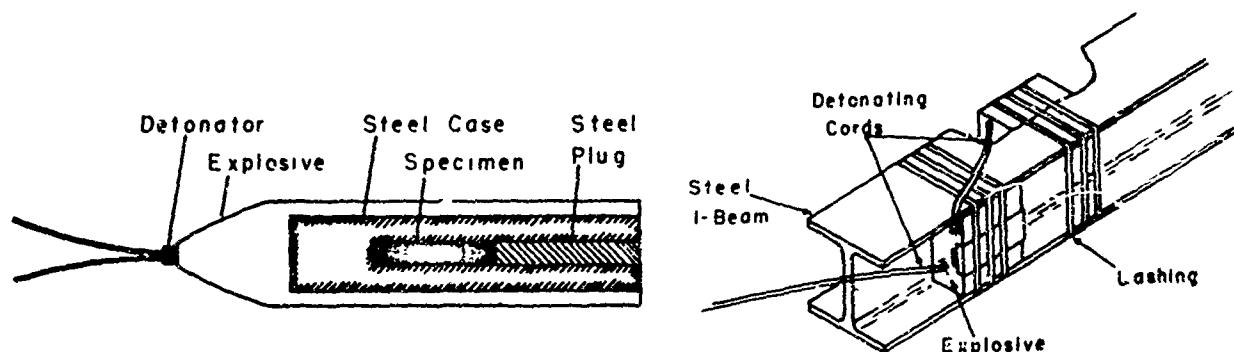
**Figure 18 Collapsing Cylinder Type
Explosive Press**

**Figure 19 Shearing an I-beam With
Contact Charges**
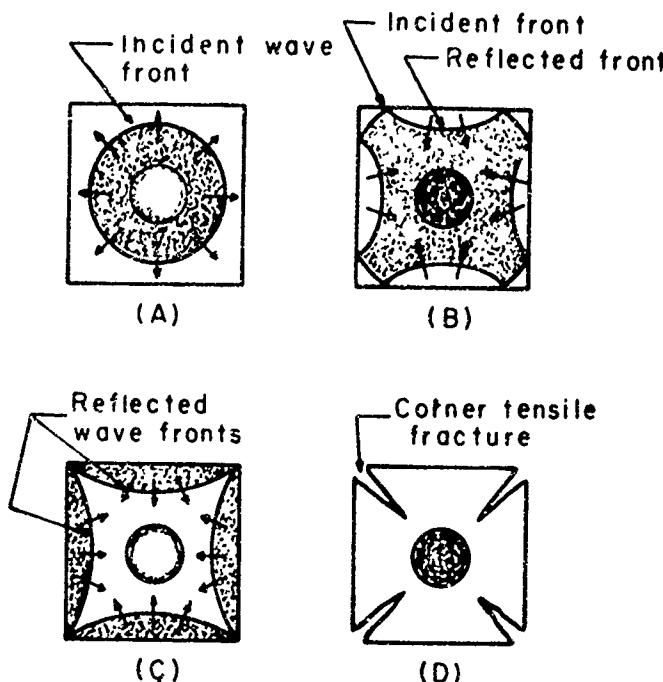
Figure 20   Cutting with Explosives
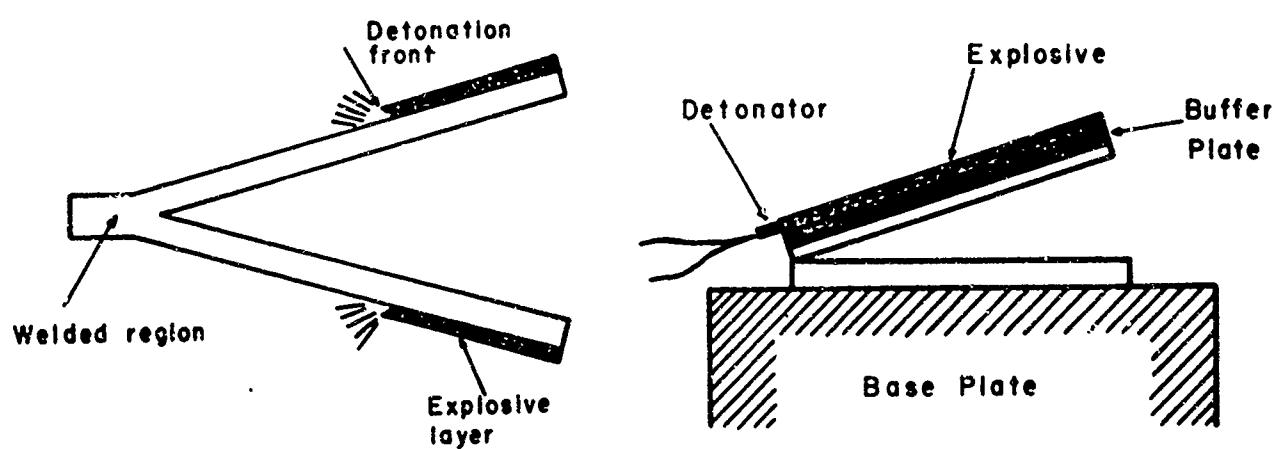
Figure 21 Experimental Arrangement for Explosive Welding of Plates

Figure 22 Cladding Operation
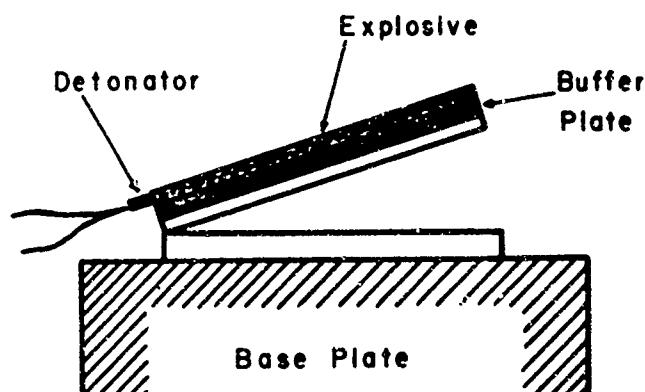
NEW METAL MANUFACTURING PROCESSES IN THE U.S.A.
OF POSSIBLE APPLICATION IN LATIN AMERICAN COUNTRIES

by

F. R. Morral

Let me begin by admitting that since this is my first visit to South America, I cannot be specifically acquainted with your plants. Therefore, I am limited to more general considerations, based on broad economic conditions. This paper concerns, primarily, manufacturing processes for steel since the steel industry is considered in all countries to be the most important.

I understand that the purpose of this meeting is to increase productivity, in order to achieve the objective of a higher standard of living for the people of your nations. Increases in productivity will be due to invention and innovations, for which, of course, research and development provide the base. These innovations and developments will have to be adapted to your own resources and related to the particular needs of your people. You will not be able to just buy a plant or adopt a material. Rather, I believe, innovation or change will be necessary in any case. In the U.S. and other highly industrialized nations, the continued improvement in manufacturing, engineering, and industry depends to a large extent on the discovery of new manufacturing techniques and equipment which reduce the cost of metal making and fabrication.

The problems I foresee are: who is to support the effort necessary to bring about innovation? How can you successfully bridge the gap between research and production? Most of your organizations are small, and so I suspect that many of your firms cannot afford to invest the capital that may be necessary to introduce technical change. In fact, companies in the various countries may wish to consider forming international industry associations to be able to do it. There is evidence pointing to a high correlation between the size of the firm and its ability to assimilate scientific information, without which innovation is impossible. No doubt this stems in part from an inadequate scientific and technical awareness by management of the smaller firms. There is also the problem of heavy capital investment by small firms.

A serious problem may be the unavailability of qualified scientists and engineers engaged in research in your countries. Two others that you have, no doubt, are: unbalance of research support in the different segments of the industry and the difficulties of communication between those doing research and those who are in a position to apply the results. If researchers cannot get the results of research across to those who can make use of them, their effort is largely wasted.

Finally, there are economic factors that have an important bearing on the diffusion of innovations within industry: the firm's rate of growth, profit level, liquidity, and other nonmetallurgical factors.

Processes Under Consideration

There are a number of alternative methods of producing useful metal shapes: (1) cast molten metal into a finished shape; (2) cast molten metal semi-continuously or continuously into ingots, bar, plate, rod, or other finished shapes, rails, etc.; (3) dissolve the ore, or concentrate, into an electrolyte and then make the finished shape by electroforming; (4) obtain the metal as powder, which subsequently is manufactured into the end shape by powder metallurgy.

Becoming more specific, metallic materials may be shaped or formed by one or a combination of the general methods indicated in Table 1. The choice depends upon the characteristics of the material, the dimensional accuracy required, and the expense permitted. Detailed information on the characteristics of these processes, their possibilities, and limitations is given in Tables 2 and 3.

Many of the difficulties encountered with the casting processes can be traced back to melting practice. The following points should be kept in mind:

(1)   Use and charge only clean material of known composition

(2)   Use only clean furnaces or crucibles for melting

(3)   Melt as quickly as is reasonably possible

(4)   Melt in a nearly neutral to slightly oxidizing furnace atmosphere

(5)   Do not superheat metal more than is absolutely necessary to insure adequate temperature as it is introduced to the mold

(6)   After removing from the furnace, skim the molten metal carefully without stirring or excessive agitation

(7)   Keep accurate temperature measurements of all melts

Foundry products generally have a poor reputation; however, by control, a great improvement can be achieved. For instance, voids caused by shrinkage during solidification are one of the primary sources of the low properties of, for example, aluminum castings. Surface defects on parts made in sand castings are common. Castells has shown that these defects can be eliminated by controlling

the pH of water-soluble constituents forming part of the sand [1]. Controlled foundry practice, proper melting and casting procedures, avoidance of oxide inclusions, proper grain-size refinement, heat treatment, and the use of radiography [3] help to produce guaranteed high-quality castings. An interesting innovation in making small castings is the self-heating crucible developed by Kemwell, Ltd., England. This consumable crucible does not require an outside source of heat and melts metals up to 3180 F. Ten pounds of many common engineering metals can be melted in 10 minutes [2].

Steel Mill Costs

Figure 1 is an outline of a traditional steel mill. Continuous casting of some steels and nonferrous metals is now done commercially (Figure 2). I note that you have already installed some units in Argentina, Mexico, Peru, and Venezuela.

A fully integrated steel mill costs between $ 350 and $ 600 per-ingot-ton-annual capacity, of which $ 60-90 per ton is for the blast furnace. Economically, then, it seems worthwhile to consider one of the many methods of iron ore reduction other than the classical blast furnace (see Table 4). Generally, these require smaller investments, have greater flexibility of operation, and often employ a larger proportion of manpower. In addition, they do not require good metallurgical coking coal, which is relatively scarce in some of your countries. Among these methods, the following are most important: electric iron smelting, low shaft smelting, and other so-called direct reduction or direct iron methods which produce, in some instances, a high-grade product equivalent to scrap, and in others, some variety of pig iron with special characteristics. In Table 5, a comparison is made of the cost per-net-ton of iron, the total investment, and investment per-ton annual capacity [4]. Note that in the rotating-furnace process, the total cost is about half that for a blast furnace of the same capacity.

The electric furnace requires only one-half as much fuel reductant per ton of iron as a blast furnace. Of this small requirement, only one-third need be lump coke and the balance can be low-volatile coal or coke breeze. The Wiberg-Soderfors furnace operates efficiently in units with outputs as low as 100 tons per day.

Steelmaking and Remelting of Sponge Iron

Steelmaking, on a small or medium scale, does not present the same problems as ironmaking. Summary cost data for both are included in Table 5.

Recently the British Iron & Steel Research Association announced FOS, a new fuel-oxygen-scrap process. This was developed successfully on a small unit. It can probably be used commercially for both small and large operations. It is

estimated that the cost of ingot making should be $ 2.50-3.00 less than with electric steelmaking on a similar scale.

Figure 3 shows melting times, operation for various methods of making steel, and some advances [5]. It may be seen that all processes are accelerated by using oxygen. Oxygen converters cut the cost of converting iron by $ 4-8 per ton or roughly, in half.

Several techniques have been developed for the removal of gases from molten steel to reduce in-plant metal losses and improve the quality of the finished product. Efficiency of process, mechanical simplicity, and flexibility of operation are usually sought. Among the various new processes adopted by some American concerns are the Ruhrstahl-Heraeus and the Bochumer-Verein Processes. Vacuum degassing has been used primarily to remove hydrogen from large ingots of forging-grade steel. The Ruhrstahl-Heraeus Process also effects removal of oxygen and some nitrogen in the production of a wide variety of forged, cast, rolled, and continuous-casting plant products. This includes low-carbon strip for the automotive industry, for which vacuum degassing has only recently been considered.

The consumable-electrode vacuum-melting process is one in which electrodes made from a primary air-melted heat are remelted by an arc process. The product thus remelted solidifies in a water-cooled copper mold under vacuum. The cost of such material in the U.S. is about five times that of air-melted steel, and I do not believe the material is of interest to you. Similar results can be more economically obtained by: (1) stream degassing, (2) ladle degassing, and (3) the Dortmund-Horder (DH) process. In essence, each of these processes involves exposure of air-melted steel to a vacuum while the steel is still in a molten state. This usually results in a lower inclusion content, particularly those inclusions considered injurious to steels-oxides, silicates, and aluminates. Alloy additions can also be made under vacuum. This permits extremely close control of chemistry and permits producing variations in chemical analysis which heretofore were impractical. These processes have, I believe, great possibilities in your countries.

Continuous Casting

Continuous casting shapes and solidifies the metal, readying it for semi-finishing in virtually one step (see Figure 2). This process, therefore, eliminates several costly steps as may be seen by comparing Figures 1 and 2 (see also Table 6). It reduces the number of personnel needed by half. For you in Latin America, it also may help solve some problems concerning ores, coke, and power.

Continuous casting may bring dramatic savings of $ 29 per ton. Capital savings run as high as 50 per cent, and it is reported that operating economies are even greater than they appear. Not only are fewer people needed, but the scrap

loss is drastically reduced so the yield is raised from about 70 to more than 80 per cent. A material with a good surface can be obtained. The Roblin-Seaway Industries Inc., at Dunkirk, New York, claim to be able to produce steel billets on their continuous unit for $ 30 a ton less than the $ 115 per ton that is the current market price for billets. Theoretical figures show that savings could be double that. The mill is expected to turn out 120,000 tons of steel this year. Estimated savings: $ 2 million a year over a conventional mill producing the same amount of steel, says Mr. Roblin, the president.

It is interesting to note that nearly 100 years ago (1865), Sir Henry Bessemer took a patent in England on pouring steel directly onto two water-cooled rollers and then withdrawing solidified plates. This technique, although not used on steel, is being used on some nonferrous metals which have lower solidification temperatures than steel. Incidentally, a modified technique is used, in which metal powder is shaped into sheet between two rolls. But more will be said about this in a companion paper.

Figure 4 is an outline of the continuous-casting installation. Although recent for steel, this type of setup has been used for semicontinuous casting of aluminum in the U. S. since the end of World War II.

Other methods have been adapted for special purposes. For critical bearings such as those used in aircraft engines, it is necessary to melt in vacuum. Induction-vacuum melting is the term applied to a process in which a cold charge is melted in an induction furnace and subsequently poured into ingots. This is essentially a small-tonnage operation.

Continuous casting of slabs for wide strip and heavy plate mills (1.5 m wide, 22.5 cm thick) has been discussed by Desfossez[6]. He describes operation of a recent continuous-casting mill in Germany and compares costs and space requirements of this with those of conventional mills.

The mold is the critical component of any continuous-casting system. There is a critical rate of descent for a billet of any given cross section. Exceeding this rate results in a solidifcation crater so deep that the skin may be warped and broken by the tensile and hydrostatic stresses exerted as the metal emerges from the mold. The rate of descent, or withdrawal speed, is further limited by the tendency of solidifying metal to stick to the mold.

Two-inch-square billets have been cast at speeds of 450 inches per minute. Figure 5 shows recent developments in the use of curved molds.

The reluctance of U. S. steel manufacturers to accept continuous casting stems from two misgivings: technologically, the process has not yet been applied to the production of all types of steel and, economically, most manufacturers are committed to operations into which continuous-casting methods are not easily assimilated.

Some plants are not ready to scrap their present, rather expensive, equipment. Now in 1964, however, National Steel announced building a mill containing the 3 devices for producing more steel at lower cost: oxygen furnaces, vacuum degassing, and continuous casting.

Continuous casting, so far, has not duplicated the combination of physical and chemical properties that characterize the "deep drawing" rimming steels. This is the type of steel used for automobile bodies, tin plate, and galvanizing sheets for many appliances. One plant in the U. S. hopes to produce a steel with good deep-drawing properties by vacuum degassing the liquid steel before it is poured into the ladle. If the steel does not have suitable deep-drawing characteristics on fabrication, failures and waste may result.

The investment in ingot-rolling machinery is so great that a profit-making primary mill of the continuous type must have a rated capacity of a million tons of steel per year. A continuous-casting plant, however, may have a much smaller capacity, so that the desired plant expansion can be accomplished in smaller increments than conventional equipment would efficiently allow.

The basic oxygen converter is best adapted to the needs of a continuous-casting machine because it can more readily supply the molten steel.

In summary, then, continuous casting offers capital savings as high as 50 per cent, with great operating economies. One company estimates an average cost of $ 10 a ton for installation and an average saving of $ 15 a ton in production costs. Under such conditions, a unit can pay for itself in less than four years. Plate and bar can be cast without the heavy-equipment blooming mill and part of the continuous mill. However, the ideal time for a producer to consider the use of a continuous-casting machine is when he is building an entirely new iron and steel mill, from blast furnaces and refining furnaces, through mill products. Thus, you, in starting, have an advantage.

Controlled Pressure Pouring

Another process which eliminates the need for a primary rolling mill, just as does the continuous-casting process, is known as controlled pressure pouring (see Figure 6) [8]. The pressure-pouring mold often is capable of appreciable adjustments in the size of the section cast. As compared with continuous casting, very good surface and greater flexibility of cast-section sizes are obtained. This technique should be of particular value to the producer of specialty steels for whom sizes and annual tonnages are small, but the number of sizes required are large, as is found in high-volume plants. This process should be of interest to tool, stainless steel, and high-quality alloy steel producers, where special shapes are required. One such special shape might be a slab of metal 1 to 2 inches thick, 20 to 40 inches wide, 60 to 96 inches long, which then would be directly worked, either hot or cold, to final size. This technicque has been very successful on some

difficult-to-work metals, such as superalloys, cobalt and nickel base, and re-
fractory metals, tungsten, etc.

To obtain the desired mechanical and surface properties due to working,
a reduction in size of at least 10 to 1 is required. Thus, the size of any precast
or continuously cast slab which is destined for a secondary rolling operation must
be kept sufficiently larger than the final bar, billet, shape, or sheet to allow
adequate working.

The concept of the operation is simple. A ladle of steel is lowered into a
chamber. A ceramic pouring tube attached to the chamber cover is placed over
the ladle and the assembly lowered until, at the sealing level, the tube reaches
within a few inches of the ladle bottom. The cover assembly is then clamped in
position by hydraulic rams, and a mold assembly is placed over the pouring tube
on top of the tank cover. Pneumatic pressure is applied to the chamber in which
the ladle rests and forces molten steel up the pouring tube into the mold cavity.
Once pouring begins, pressure is somewhat reduced to control the rate of flow.
When the mold is filled, a special stopper arrangement seals off the pouring tube
from the mold and the pressure is then reduced to normal in the ladle chamber.
Either the ladle chamber or the mold will then move away, depending on plant
design, and another empty mold will be sealed on the top of the pouring tube; the
process then is repeated. The entire cycle is rapid, a matter of a very few
minutes, and size changes in the mold are compensated for by use of differing
pouring-tube sizes. The large mold, for example, is fed at a much greater rate
per minute than are small wheel molds.

Several years ago, an interesting process using pig iron was developed by
Stora Kopparbergs Bergslag A. B. [9]. The process (see Figure 7) consists of
mixing 85 per cent granulated pig iron and 15 per cent high-purity iron ore con-
centrate. The mixture is packed in a box made of thin sheet steel and decarburized
at 1100 C. Then, at 1100-1200 C, the box of granules is run in a standard rolling
mill. This sheet shows good deep-drawing properties and welds normally. It can
be produced for an estimated $10-20 per ton less than for steel sheet made by con-
ventional methods.

Properzi System - for Rod and Wire

For continuous casting and shaping of nonferrous metals such as lead, alu-
minum, copper, and zinc, the Properzi system (see Figure 8) is interesting. Three
units are now operating in Latin America, producing conductor-grade aluminum rod.
Two models are available: on the small unit, 3,700 pounds per hour of 3/8-inch-
diameter E.C. aluminum rod can be produced; while on the large unit, up to 9,000
pounds per hour can be produced. On this unit, also, about 10 tons per hour of cop-
per rod can be produced. In some quarters, it is believed that this method of pro-
ducing conductor redraw rod will render obsolete the now conventional method[7].

The unit consists of two major pieces of equipment -- a rotary casting machine and the hot-rolling mill in tandem with the casting machine. The ring mold of the casting machine consists of a groove, roughly triangular, machined in copper, bounded over an arc of 150 degrees by an endless steel belt which forms a flat side (the top) of the mold. Molten metal moves from a holding furnace and passes through a cast-iron spout where the metal is deposited onto the wheel. This rotates in a clockwise direction. The sheeted metal passes through a water-cooling sequence, then leaves the casting wheel as a solid at the 7:00 position.

The wire emerges from the 17th stand at a diameter of 0.300 inch. Larger sizes of wire can be made by reducing the number of stands used.

A wide variety of problems can occur during solidification -- laps, seams, splits, fins, large slivers, scabs, roll marks, neckdowns, enfolding, or off-round. Smeared or embedded oxides also may be visible. Laps, scales, folds, cracks, and covered seams occur just below the surface.

These problems must be detected and controlled to produce quality products. The cost of a unit is about $ 450,000 for the caster, furnace, and supporting equipment. No licensing or royalty payments are involved (Steel, March 30, 1964, p 133).

Working

In 1938, the Krause mill was proposed [10]. It was then ahead of its time, but now bears careful consideration particularly because of the new materials available for rolls. Figure 9 shows the principle of operation. The heavy plate is introduced between two rolls which are forced to come closer together as they move along the inclined plane, thus essentially drawing and rolling the small bite of the plate taken and forcing reduction.

The use of sonic and ultrasonic vibration in controlling grain size during solidification of steel and nonferrous metals may be of interest to you. A recent summary report indicated that, for U. S. producers, grain refinement by sonic or ultrasonic treatment may not be economically attractive for steels going into everyday applications. It could however, be a very acceptable method for avoiding or minimizing undesirable properties attributed to banded structure. Incidentally, this technique seems to hold much promise for grain refinement of weld metals. Considerable work, both of a fundamental and practical nature, is necessary.

In the past few years, a number of new forming techniques have been developed. They are listed and compared with conventional techniques in Table 7. In a study of hard-to-form materials it was found that some showed increased formability at high velocity (up to 1000 ft/sec). Ductility was higher for some of these materials when this forming was done at temperatures other than room temperature. (W. W. Wood, Product Engineering, September 30, 1963, p 713). In ad-

dition, stainless alloys, light alloys, superalloys, and refractory alloys (Mo, W, 10-10 Cb) were tested.

The application of ultrasonic energy to conventional metalforming and melting operations is sufficiently promising that the technique merits your attention[11]. Data indicate that ultrasonic energy offers metalworking greater speeds, lower forces, and improved surface finishes.

These new high-energy-rate methods require considerably lower capital investments, produce parts to closer tolerances and with unusual material properties, and offer the ability to form high-strength and even brittle materials. The distinguishing characteristic is that work is performed during a rapid release of energy Some of the techniques require special precautions, but the advantages far outweight the hazards.

Liberating large amounts of energy at high rates can produce different effects on different metals. High explosives, propellants, gas mixtures, and high-pressure gas may be used in explosive-forming techniques. In the electric-discharge type of high-velocity metalworking techniques, three processes have been developed: (1) exploding wire, (2) spark discharge (see Table 7), and (3) magnetic field. The forming can be done in either a liquid medium or in air. The working velocity in these techniques is greater than 30 feet per second (see Table 7). In addition to metal forming, these techniques have found use in hardening, welding, metal removal, and powder compaction.

High-energy-rate forming (HERF) has permitted cost savings of 30-50 per cent. Difficult metals, thin walls, fine tolerances, and complex shapes are formed in a single blow.

Electric-spark forming is now a production tool in the U.S.A. A prime feature in the economics of this process is tooling, which saves half the cost. This process will make complex, even severe, shapes to fine tolerances. Spark forming makes parts in a 10-second cycle. Cleaning, after forming, is possible in operation because the spark energy and shock wave homogenize oil in water.

Magnetic forming has a good chance in the production of small parts. In tube expanding or swaging, shape control is excellent and there is no springback.

Ausforming, a thermomechanical process, is of particular interest because of the good properties obtained. Data obtained on several steels will be presented in a companion paper. The steel is deformed while it is still austenitic (in the unstable austenite range) and then allowed to transform to martensite. A high strength level, together with satisfactory ductilities, is obtained.

Heat Treating

To develop the maximum properties of an alloy, heat treatment may be necessary. These may be classified as follows:

Steels (see Figure 10)	Other Alloys
Annealing: process, stress-relief, bright, "cyclic"	Solid-solution treatment
Normalizing	Precipitation treatment or aging
Austenitizing	
	Cast Iron
Hardening: patenting, austempering martempering, ausforming	Malleabilizing
Tempering	
Carburizing	
Nitriding	

I have been actively engaged in heat treating metals and alloys in salt baths. About 15 years ago, I became convinced that this processing technique had great possibilities because it could be applied to small or large processing runs. Although control is necessary, it is not difficult[12]. A basic knowledge of the chemistry permits use of simple means of control which will minimize any difficulties [13] (see Tables 8 and 9). Salt baths are a dependable and economical method of heat treating. Heat transfer is rapid and the process is applicable to most metals. It should be suitable for the new techniques of austempering, ausforming, and martempering steels.

Salt baths are useful for cleaning surfaces which have refractory oxide films. The chemical surface may be changed by carburizing, decarburizing, and cyano-nitriding. Other elements may also be applied to the surface by the use of salt baths and may be encouraged to diffuse into the surface of the part.

Machining

Machining is a well-known manufacturing process. New and unconventional techniques are given below:

Principle	Process
Electrical-discharge machining	Vaporization of workpiece by high-frequency electric sparks

Principle	Process
Electromechanical machining	Electrolyte dissolves reaction products formed on workpiece by electromechanical action
Chemical milling	Controlled attack of workpiece with su..able chemical reagents
Ultrasonic machining	Abrasive particles activated by tool vibrating ultrasonically remove workpiece material by impact
Electron-beam machining	Vaporization of workpiece by impinging high-energy electron beam
Plasma arc (and laser) machining	Melt metal, blow metal out of groove by angling torch

Powder Metallurgy

Powder metallurgy was long considered an expensive method limited to relatively small shapes because of pressures required. However, there is now renewed interest in this process. Table 10 lists its advantages. Metal parts are formed by compacting metal powders to a certain shape and size and then sintering the compact at elevated temperatures (below the melting point of the main component) in order to obtain a material of the desired physical properties.

Frankly I envy you engineers operating in Latin America. You have ahead a wonderful opportunity to use your creativity and know-how as you design and make operative new industries and adapt processes best suited to your local conditions, raw materials, power sources, needs, and economics. With largeness comes a certain restriction of innovation, with specialization comes a narrowing. It is in this younger stage of development, in which you now find yourselves, that the most ingenious and creative work can be done. Your creativity and skill today can bring great economic and technological advances to your countries.

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TABLE 1. METHODS FOR SHAPING OR FORMING MATERIALS

I. Casting While Liquid Into Molds
- (A) Gravity casting (with little or no added pressure)
    1. Sand (green and dry), shell, plaster, investment-casting mold
    2. Semipermanent molds
    3. Permanent molds
- (B) Centrifugal casting-symmetrical or small unsymmetrical objects
- (C) Direct casting or continuous casting of plate, sheet, bar, or rod
- (D) Die or pressure casting

II. Working (Hot or Cold), Heading, Piercing, Drawing (Wire, Tubing), Cupping, Forming, Spinning
- (A) Hot-rolling mills -- blooming, billet, continuous, or Morgan mills (two-, three-, or four-high cluster mills)
- (B) Cold rolling -- continuous, tandem, Steckel, Krause
- (C) Forging -- hammer, press, or die (open, closed), upset swaging

III. Extruding (while in a very plastic condition at a suitable temperature either just below the melting range or, with some metals, close to room temperature)
- (A) Hot extrusion
- (B) Cold extrusion of Hooker process
- (C) Impact extrusion

IV. Miscellaneous
- (A) Stamping
- (B) Machining
- (C) Electroforming
- (D) Powder metallurgy (May use extruding or roll compacting)
- (E) Joining -- soldering, brazing, welding

TABLE 1. METHODS FOR SHAPING OR FORMING MATERIALS

TABLE 2a. DESIGN FEATURES OF METAL FORMS

Form	Choice of Materials	Complexity of Part	Maximum Size	Minimum Size	Mechanical Properties	Precision, Tolerances	Special Structural Characteristics	Surface Smoothness	Surface Detail	Remarks
Sand Castings	Wide—ferrous and non-ferrous metals	Considerable—holes, bosses, / seating pads	Great—largest forms made are sand castings	¼ in. is smallest practicable section	Fair to high depending upon metal cast	±¹⁄₁₆-¼₂ in./in., closer at extra cost	Good bearing structure	Poor	Poor	Usually require some machining before use
Shell Mold Castings	Wide—same as above excepting low carbon steels	Moderate—limited by mold removal problem	<60 in. square. Rest for smaller parts	¹⁄₁₆-in. sections	Good—little porosity, few gas inclusions	±0.003-0.005 in./in.	High quality for cast metals	Good	Good	Considered best of low cost castings
Permanent Mold Castings	Restricted—brass, bronze, aluminum	Limited—restricted by use of rigid molds	Moderate—50 lb is practical limit in aluminum	1-oz. sections as thin as 0.1 in.	Good—high in centrifugal castings	±0.01-0.05 in.	As above	Good	Good	Large quantities allow production economies
Plaster Mold Castings	Narrow—brass, bronze, aluminum	Considerable—mold destroyed in removal	Moderate—up to 15 lb in most materials	Small—¹⁄₃₂-in. sections possible	Fair	±0.010-0.005 in.	—	Good	Good	Little finishing required
Investment Castings	Wide—includes materials hard to forge or machine	Considerable—very few limitations	Moderate—best for parts under 2 lb	Small—sections down to 0.030 in.	Good	±0.005 in./in. common, ±0.002 in./in. possible	High quality for cast metals	Excellent	Excellent	Best for parts too complicated for other casting
Die Castings	Narrow—zinc, aluminum, brass, magnesium	Considerable—though cavity dies might be required	Large—up to 75 lb in aluminum, 200 lb in zinc	Sections as small as 0.025 in.	Fair	±0.001 in./in.	Special properties can be obtained through use of inserts	Good	Good	Most economical where applicable
Drop Forgings	Medium—many ferrous, nonferrous alloys	Moderate—limited by die restrictions	Large	Small as fraction of an ounce	High	±0.010-0.030 in. without joining	Grain flow provides toughness	Fair	Fair	Used where high strength is required
Press Forgings	Medium—best for nonferrous alloys	Limited—but greater than drop forgings	Large—300-400 lb practical maximum	Smaller than drop forgings	High	±0.005 in	Hot working gives structural advantages	Fair	Fair	Closer tolerances and greater complexity than drop forgings
Upset Forgings	Medium—many ferrous, nonferrous alloys	Limited to cylindrical shapes	Medium—9-in. bar about largest	Moderate—not comparable to casting	High	Medium—compare to press forgings	Grain flow provides toughness	Medium	Medium	Best suited to small parts
Cold Headed Parts	Narrow—confined to steel, highly ductile alloys	Limited—less flexibility than forgings	Small—7 in. by ½ in. dia usual maximum	Small—¼-in. dia parts can be made	High	±0.010 in. common, ±0.002 in. possible	Tough structure	High	Fair	High production rates
Continuous Cast Parts	Narrow—bronze, nickel bronze	Limited—can be complex in cross section only	Moderate—9 in. max dia	Moderate—¼-in. for sections	Good to high depending on alloys	±¼-in. closer on rounds	High quality for cast metals	Good	Only as part of contour	Provides long section and complex shapes
Extrusions	Restricted—light metals, some steels, copper, titanium	Limited—can be complex in cross section only	Medium—8 to 10 in. max dia	Small—0.050-in. sections in aluminum and magnesium	Good	±0.005 in. common	Grain flow improves properties	Good	Only as part of contour	Sometimes used as blanks for other processes
Impact Extrusions	Narrow—aluminum, magnesium, some steel	Limited—must be concentric	Small—6 in. dia soft alloy, 4 in. in hard	Moderate—¼ in. dia smallest	High—metal cold worked	±0.001 in. common	Grain flow improves properties	Good	Good	Can eliminate machining
Roll Formed Shapes	Narrow—cold rolled steel, some aluminum	Restricted to thin and uniform cross sections	Large	Sections from 0.125 in. up	Good	±0.002 in. common	Cold work improves properties	Good	None	Requires large quantities
Stamped and Press Formed Parts	Wide—all workable metals	Moderate—some design restrictions	Large	Small—sections as thin as 0.003 in. possible	Good to high	Good—to ±0.001 in. common	—	High	Good to excellent	Extremely low cost in quan, otherwise moderate
Metal Powder Parts	Moderate—iron, steels, nickel, brass, nickel alloys, refractory metals	Limited—powders flow poorly, do not transmit pressure	Small—parts less than 4 in. square best	Small—<¾₆ in. dia possible	Fair to good	Good—±0.001-0.005 in. common	Porosity can be controlled and complex materials formed	Fair	Fair	Can use materials not formable by other processes
Spinnings	Wide—many sheet metals	Limited—cylindrical or concentric shapes	Large—up to several feet in dia	Moderate—¾ in. dia in gages less than 0.040 in.	Good	Fair—±0.015-0.060 in. common; better at added cost	Grain flow, cold work improve properties	Good	None	Good for large pieces or short runs
Screw Machine Parts	Wide—best suited to highly machinable metals	Moderate—limited to rotational shapes	Medium—up to 6 in. long, 2¾ in. dia	Small—<¹⁄₁₆ in. dia	High	±0.001-0.005 in. possible	—	Excellent	Good	High production rates, low cost
Electroformed Parts	Narrow—iron, copper, nickel, silver	Great—extreme complexity possible	Limited—¾-in. sections can be built up	Small—0.005 in. or less	Fair—lower than wrought	High—±0.002-0.0002 in. common	—	Excellent	Excellent	Best when complexity and accuracy essential
Tubing	Wide—any ductile metal available in tubular form	Limited by sectional shapes of tubing	Usually 4 to 6 in. o.d.	Moderate—¾ in. o.d.	Good—cold working improves properties	Good—depends on quality of tubing	Grain flow improves properties	Good	None	Good means of reducing costs
Welded and Brazed Parts	Wide—dissimilar metals can be joined	Great—extremely complex shapes	Unlimited	Moderate	Variable—depends upon components	Medium—not highly precise	Can combine parts with special properties	Depends on components	None	Often needed to meet design requirements

TABLE 2b. COMPARATIVE DATA TO PROCESS HOLLOW OR SOLID NONCONCENTRIC SHAPES[a]

RELATIVE PROCESS COSTS: IN PRODUCTION QUANTITIES

	PROCESS	PIECES PER HOUR	TOOLING (Low–High)	LABOR	MAT'L WASTE	10	100	1000	10,000	100,000
C	Sand	1 to 20 up to 30								
A	Die	20 to 300 up to 550								
S	Centrifugal	1 to 5 up to 50								
T	Permanent mold	10 to 360								
I	Shell molding	10 to 75								
N	Investment	80 to 1500/day								
G	Plaster mold	5 to 10								
	Powder metallurgy	100 to 4000								
	Impact extrusion	500 to 7200								
	Continuous extrusion	2 to 700 ft/min								
	Roll forming	50 to 250 ft/min								
	Electro forming	Note 2								
	Brake forming	5 to 500								
	Die forging	10 to 500								
	Roll forging	1000 to 3000								
	Stamping	To 12,000								
	Wire forming	1500 to 30,000								
	Contour forming	60 to 100								
	Planing	—								
	Broaching	3 to 2000								
	Flame cutting	To 60 in./min.								
	Shaping	1 to 6								
	Milling	1 to 100								
	Contour sawing	2 to 20								

(a) Ref: Product Engineering, March 2, 1964, 48-49.

TABLE 3. GENERAL CHARACTERISTICS OF CASTINGS

Type	Cost				Time[c]	Size			As-Cast Finish, rms[e]
	Labor	Equipment[a]	Material	Typical Pouring Rate, per hr[b]		Range	Avg. lb[d]	Min Section Thk, in.	
Sand	High	Die low, tooling high, pattern ¼ of die	Low	25	3-15 days	<1 oz to >200 tons	Few ounces to several tons	Special—¹⁄₁₆, small—½-⅛, large—³⁄₁₆-¼	Requires grinding, polishing, buffing
Precision Sand	Medium high	Low	High	300 per month	4-6 weeks	Max size not known. Present — <1 lb weight to 6 ft length	1-4	0.050	75-80
Permanent Mold	Medium	High	Nonferrous—high, gray iron—low	30	6-12 weeks	1 oz to 600 lb	1-10	0.090	100-125
Plaster Mold	Medium high	Low	High	4-5	4-6 weeks	<1 oz to >100 lb	3-5	0.040-0.060	50
Investment	High	Varies with quality of pattern die necessary	Wide range	Generally low; higher with plastics pattern	4-6 weeks	<1 oz to 25 lb —wax or plastics; >100 lb—frozen mercury	Up to 1	0.030	50 — wax and plastics; 40—mercury
Die	Low	High	High	75-150 aluminum, magnesium, copper-base; 300-350 z.	8-14 weeks	<1 oz to 75 lb aluminum; <1 oz to 200 lb zinc	½-1	0.050	50

[a] Dies, patterns and/or machines.
[b] These figures are general for one set of equipment. Actual rate of casting production depends on number of cavities per mold.
[c] From complete design to production.   [d] Average size of competitive castings.   [e] Finish obtainable in limited areas.

TABLE 4. IRON MAKING PROCESSES

I.	Smelting	Shaft Furnaces	Conventional blast furnace: low shaft furnace (Demag-Humbolt) +
		Electric Furnaces	Tysland Hole*; Lubatti*; deSy Ghent $^+_+$
		Electric Furnaces with Pre-reduction	Strategic-Udy*; Orcarb$^+_+$ Dwight-Lloyd-McWane$^{+}_+$
		Rotary Kiln	Basset*; Stora Kopparbergs Bergslag
II.	Flash Smelting		Flame Smelting (Cyclosteel)$^+_+$; Jet Smelting$^-_+$; Diamond Alkali
III.	Direct Reduction (gas reductant)	Shaft Furnace	Wiberg-Soderfors: Lurgi Galluser$^+_+$
		Retort	Madars$^+_+$; HyL*
		Fluid Bed	Esso Little*; Nu-Iron+; Armco H-Iron+; Stelling+; Magrigal
IV.	Direct Reduction (solid reductant)		Tunnel kiln (Hoganas-Sieurin)*; Krupp-Renn; Bureau of Mines; R-N+; Bruckner*; Urquehart$^+$

*Commercial   +Semi Works   ‡Pilot

Source: Iron & Steel, Dec. 1963, p 586

TABLE 5.   COST COMPARISON OF VARIOUS PROCESSES

	Cost per Net Ton	Total Investment or Ton-Year	Operating Costs	Remarks
A. Iron Processes				
Wiberg Sodefors	$62	$1,600,000		1958
Hy L		$30	$10	1958
Krupp-Renn	$40-46	$42-50		
R-N	$43	$19,500,000	$4	
Strategic-Udy				
Submerged arc				300 t/day
Electric		$60-75		For 800 t/day
Rotating furnace		$2,000,000		For 130 t/day
Stora-Koppar-bergs Bergslag)				
B. Steel Processes				
L-D		$23-39		
Basic hot-blast				
Cupola	$40-50	$7-10		70,000 t/yr or more
Kalds process				
FO$_2$S (Bisra)				
Plasma arc melting				

Sources:

G. P. Contractor and W.A. Morgan, Iron & Steel, December 1963, pp 586-591

Iron Age, October 31, 1963, pp 104-105

Fuel-oxygen-scrap process (Metalworking, January 14, 1964, p 6)

G. Magnolo, The Canadian Mining & Metallurgical Bulletin, January 1964, pp 57-62

TABLE 6. COMPARISON OF CONVENTIONAL AND CONTINUOUS CASTING

Conventional Casting	Continuous Casting
Melting furnace	Melting furnace
Ladle	Ladle
Crane transport to casting area	Crane transport to casting area
Ingot molds	Continuous casting machine
Rail transport to stripper	Semifinished products
Stripper	
Rail transport to soaking pits building	
Crane to soaking pits	
Crane to blooming mill	
Blooming mill	
Semifinished products	

TABLE 7. COMPARATIVE RATES OF ENERGY RELEASE

Type	Equipment size	Time, sec.	Power, ft-lb/sec	Remarks
Press	80 in/min, 1 in. stroke, 660 ton	0.75	158,000	
Hammer	180 in/sec, 1 in. stroke	5.6×10^{-3}	20,000,000	
Pneumatic Mechanical	1200 in/sec, 1 in. stroke	8×10^{-4}	140,000,000	
Electrospark (in liquid or air)	150,000 joules	4×10^{-4}	280,000,000	Spark discharge: Spark jumps across electrodes submerged in fluid; creates shock wave. Exploding wire: Wire between electrodes vaporizes and converts to plasma, creating a shock wave.
Explosive (in liquid or air)	0.26 lb	2.5×10^{-5}	4.4 billion	High velocity pressure wave caused by explosive deforms workpiece at high strain rate.
Electromagnetic Metal Forming				Rapidly changing magnetic field causes forces which move workpiece into die.

Note· 1 ft-lb/sec = 1.82×10^{-3} HP = 1.36×10^{-3} Kw.

TABLE 8. COMPOSITION OF COMMONLY USED HEAT-TREATING SALTS
(Specification Mil. S-10699A)

| | Constituent, wt % | | | | | | | | |
Class	NaNO$_2$	NaNO$_3$	KNO$_3$	Na$_2$CO$_3$	NaCl	KCl	BaCl$_2$	BaCl$_2$ plus SiO$_2$	CaCl$_2$
1	37-50	0-10	50-60						
2		45-57	15-57						
3				45-55		45-55			
4					15-25	20-32	50-60		
4A					10-15	25-30	40-45		15-20
5					40-60	40-60			
6						5-15	85-95		
7								98 min*	
8					3-7		93-97		

*Class 7 salt shall be supplied in four forms containing the following amounts of rectifier, as specified: 7A--No silica; 7B-0.25 to 1.25 silica; 7C--1.5 to 2.5 silica; 7D--4.0 to 5.0 silica.

TABLE 9.   WORKING RANGE AND PRINCIPAL USES OF SALT BATH
          LISTED IN TABLE 8

Class	Working Range, F	Principal Use
1	325 to 1100	Quenching and tempering steel
2	550 to 1100	Heat treating aluminum. Annealing and stress relieving of copper alloys
3	1150 to 1700	High-temperature tempering of low carbon steel. Annealing copper alloys
4	1100 to 1650	Wide temperature-range hardening and annealing of carbon steel
4a	1025 to 1400	Hot quenching and tempering of high speed steel
5	1300 to 1650	General heat treatment of carbon steels. Pre-heating bath
6	1650 to 2000	Annealing of stainless steel. Hardening high carbon-high chromium tool steels
7	1900 to 2400	Hardening high speed steels and certain high alloy steels
8	1650 to 2350	Hardening high speed steel and high carbon-high chromium steels

The composition range of the eight classes of heat-treating salts are given in Table 8.
Table 8 is useful for government purchasing but I prefer a more inclusive classifi-
cation, as follows:

1.   Low-melting salts: oxidizing Class 1 and 2 (Mil. S-10699a)
2.   Carbonate salts: alkaline, includes Class 3
3.   Case-hardening and carburizing salts: cyanide mixtures
4.   Neutral salts: (a) alkali metal chlorides, Class 5
                    (b) alkaline earth metal chlorides, Class 4, 4a, 6, 7, and 8
5.   Miscellaneous: Caustic mixes, glasses, etc.

TABLE 10. ADVANTAGES OF POWDER METALLURGY

1.   <u>Applications properties</u>   2.   <u>Production</u>

   Close tolerances   Mass-production process

   Density control   Fewer operations

   Weight control   No scrap loss

   High wear resistance   Cost reduction

   Self-lubrication   Minimum machining

   Parts may be plated   Minimum finishing

   Parts may be hardened

Electric-arc furnace • Ladle • Ingot moulds • Stripper • Soaking pits • Grinding • Reheating furnace • 2-high roughing mill • 3-high finishing mill • Hot-rolled strip • Blooming mill

29 men | 26 men | 16 men | 32 men

Total Manpower – 103
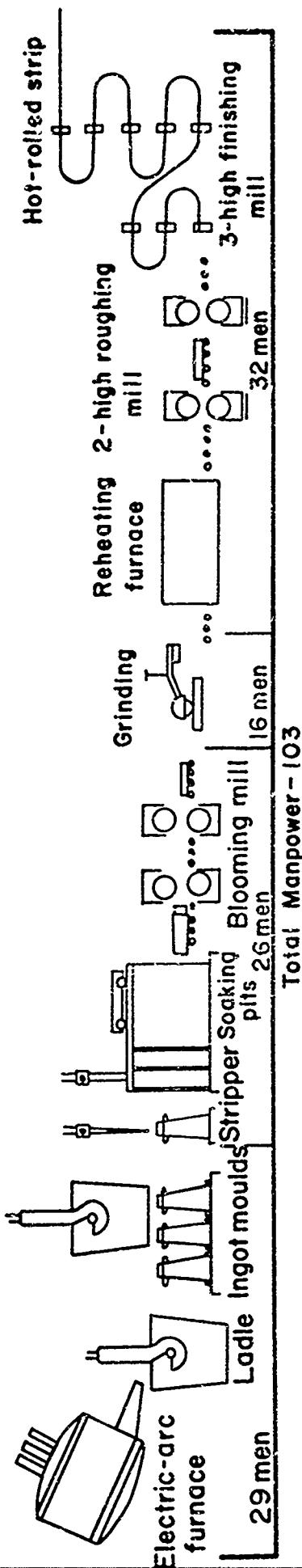
Figure 1   Schematic Diagram of a Steel Plant Using Arc Furnaces and Conventional Ingot and Rolling Facilities

Electric-arc furnace • Ladle • Continuous casting machine • Reheating furnace • Flame descaming • 2-high roughing mill • 3-high finishing mill • Hot-rolled strip

13 men | 8 men | 1 man | 2 men | 27 men

Total Manpower – 51
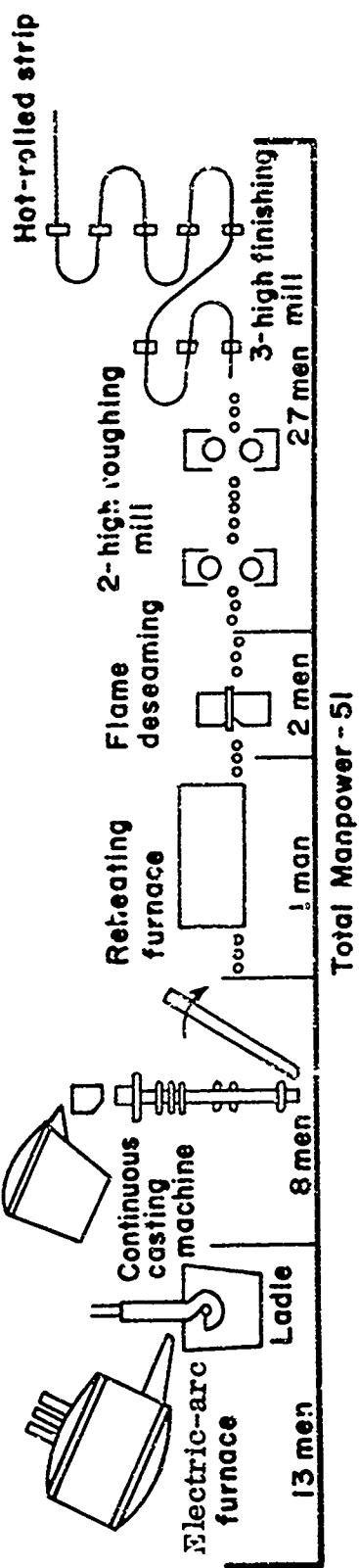
Figure 2   Schematic Diagram of a Steel Plant Using Arc Furnaces and Continuous Casting Facilities
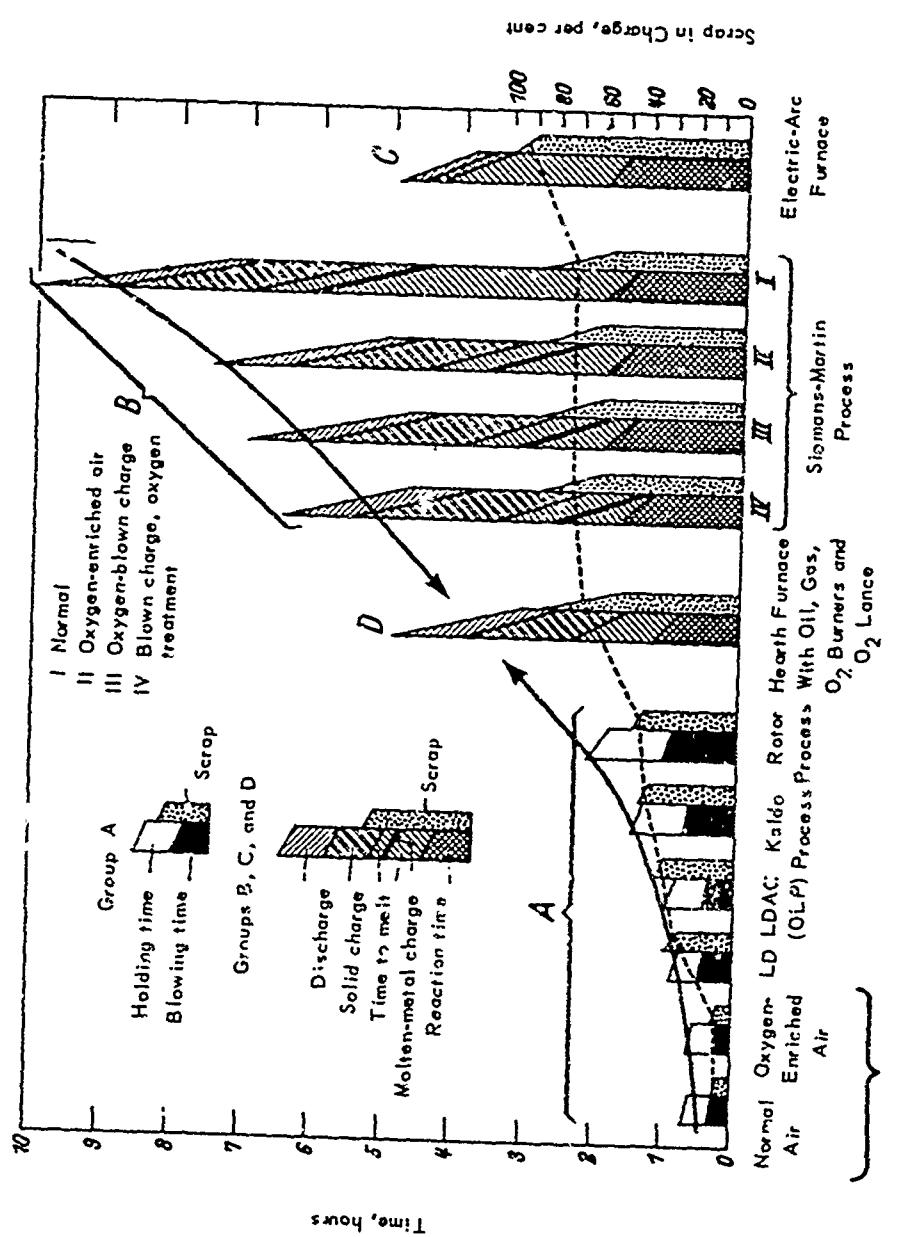
Figure :   Comparison of Steel-Production Processes
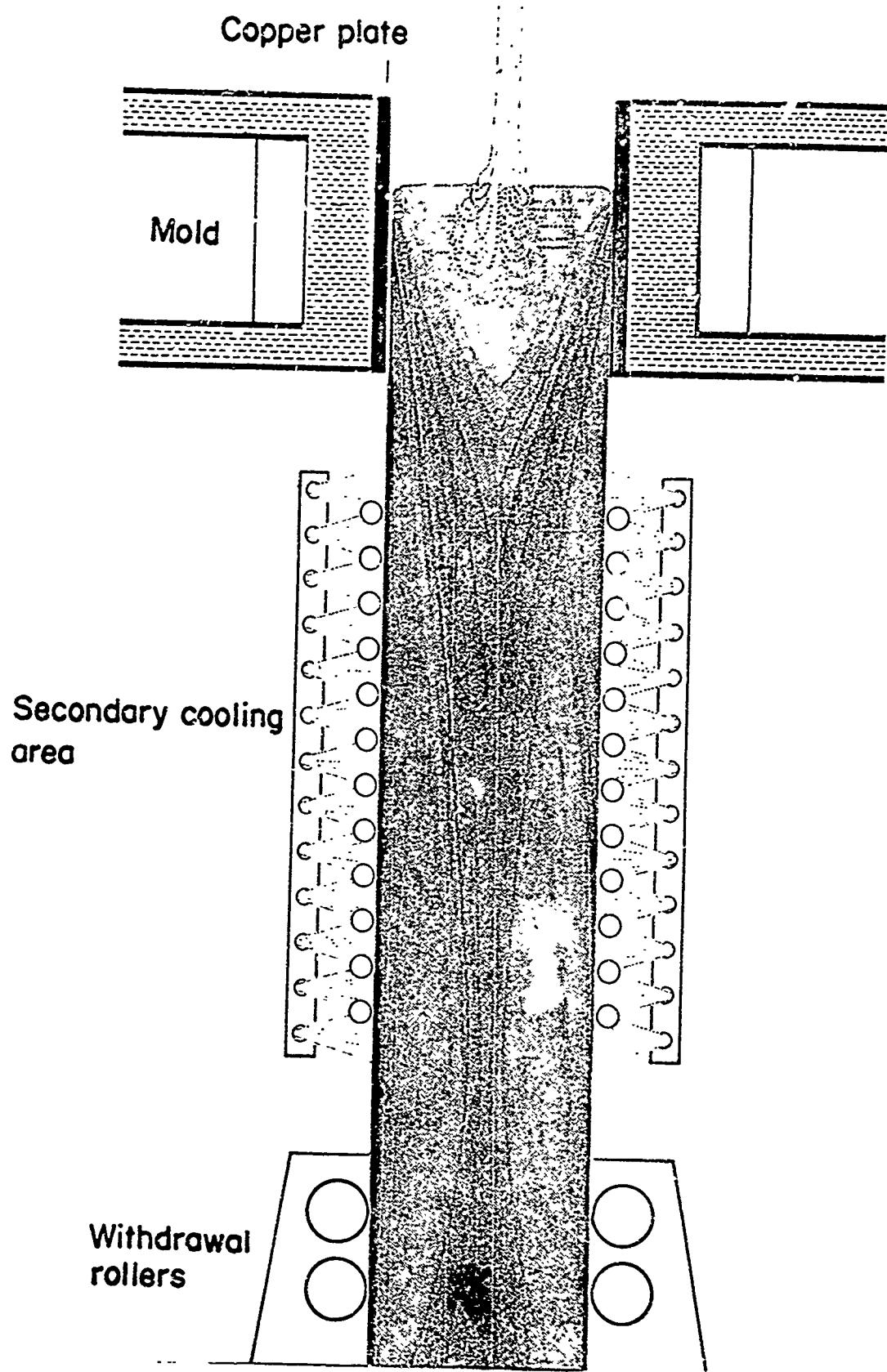
Figure 4   Continuous Casting of Steel
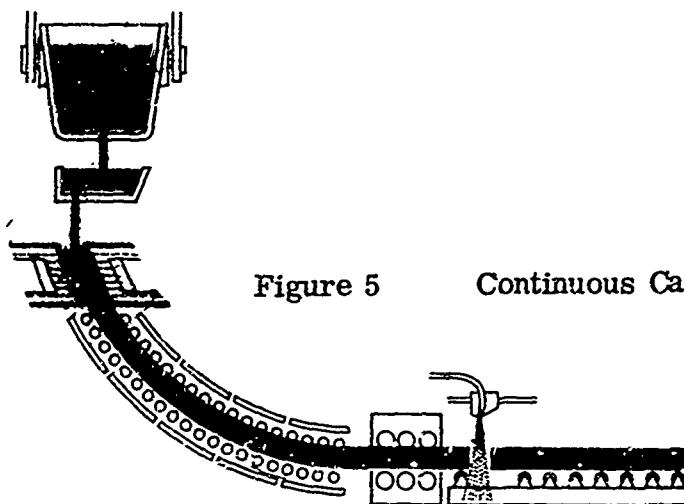
Figure 5   Continuous Casting of Steel

Plunger

Graphite mold

Cover

Foundry floor level

Controlled air pressure

Ceramic spout

Steel

Air-tight chamber

Insulated ladle
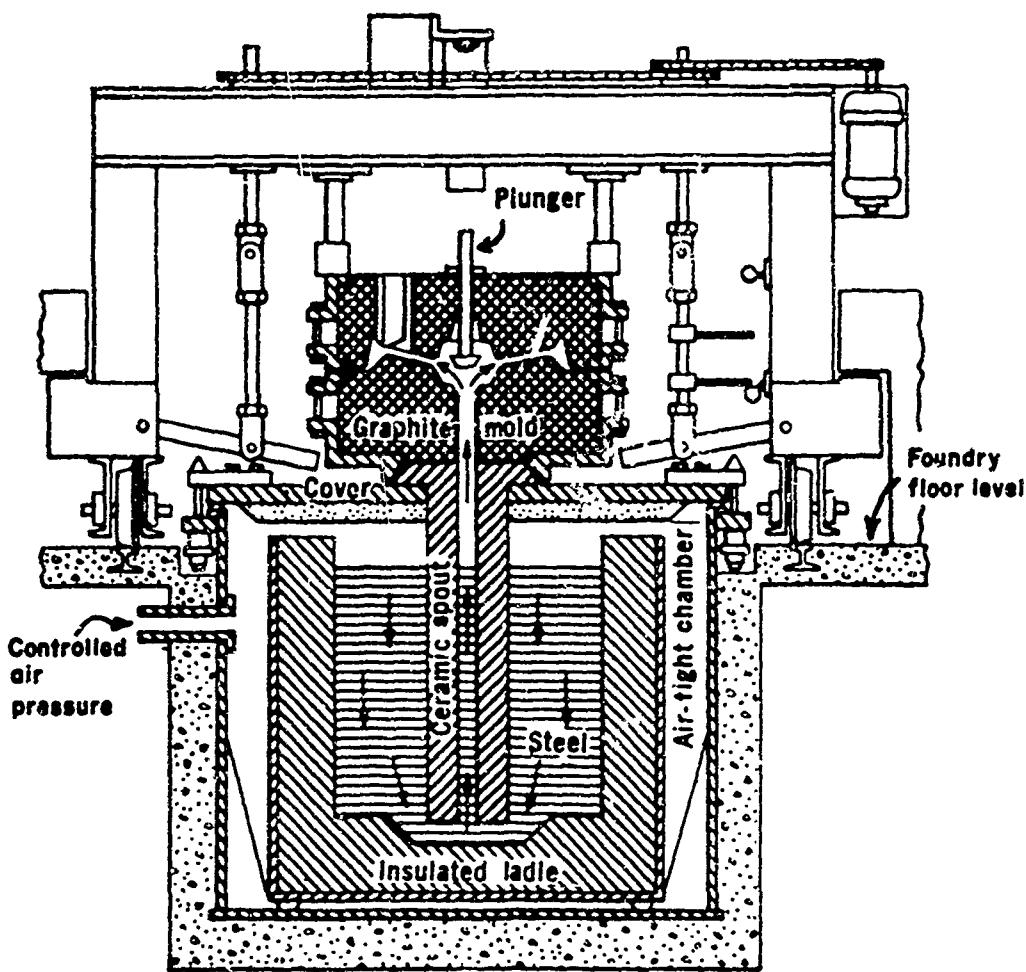
Figure 6   Process for Controlled-Pressure Pouring of Wheels
With Suitable Molds the Process can be adapted to
the Production of Steel Slabs
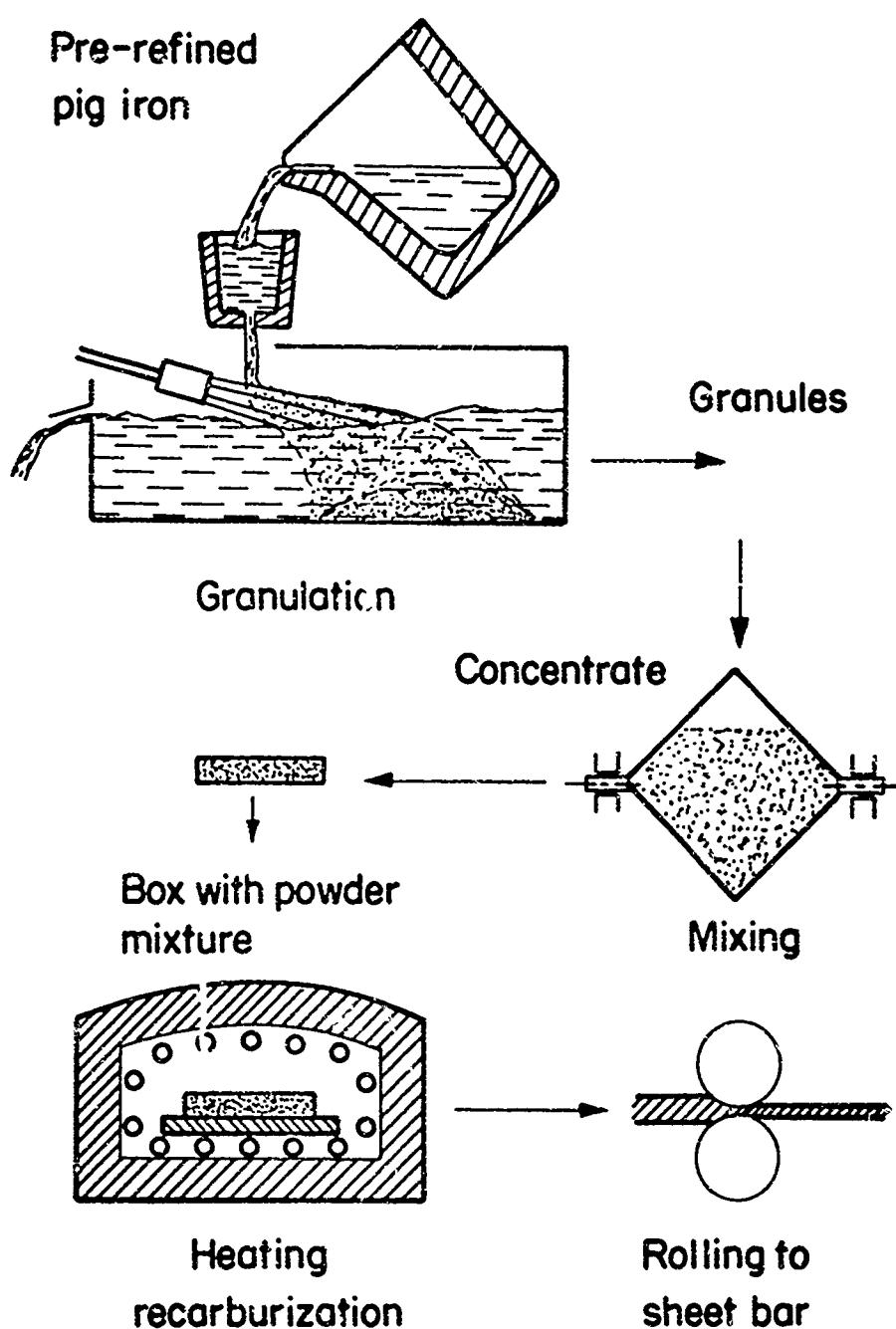
Figure 7   Steps in a Powder-Steel Process
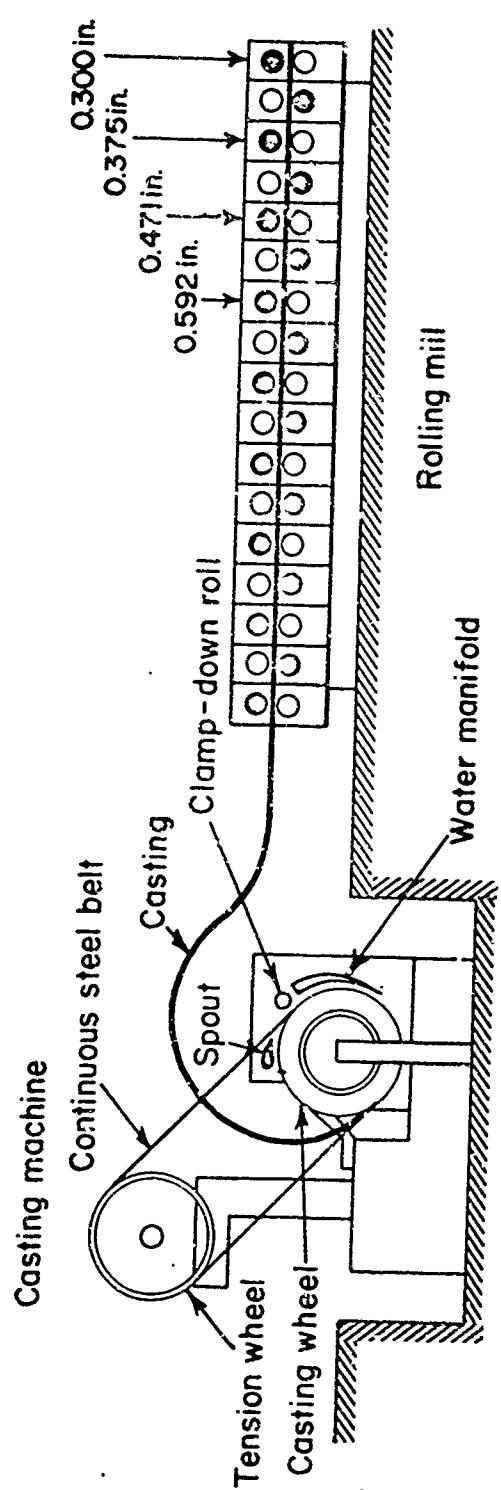
Figure 8   Casting Round Wire by the Properzi Process
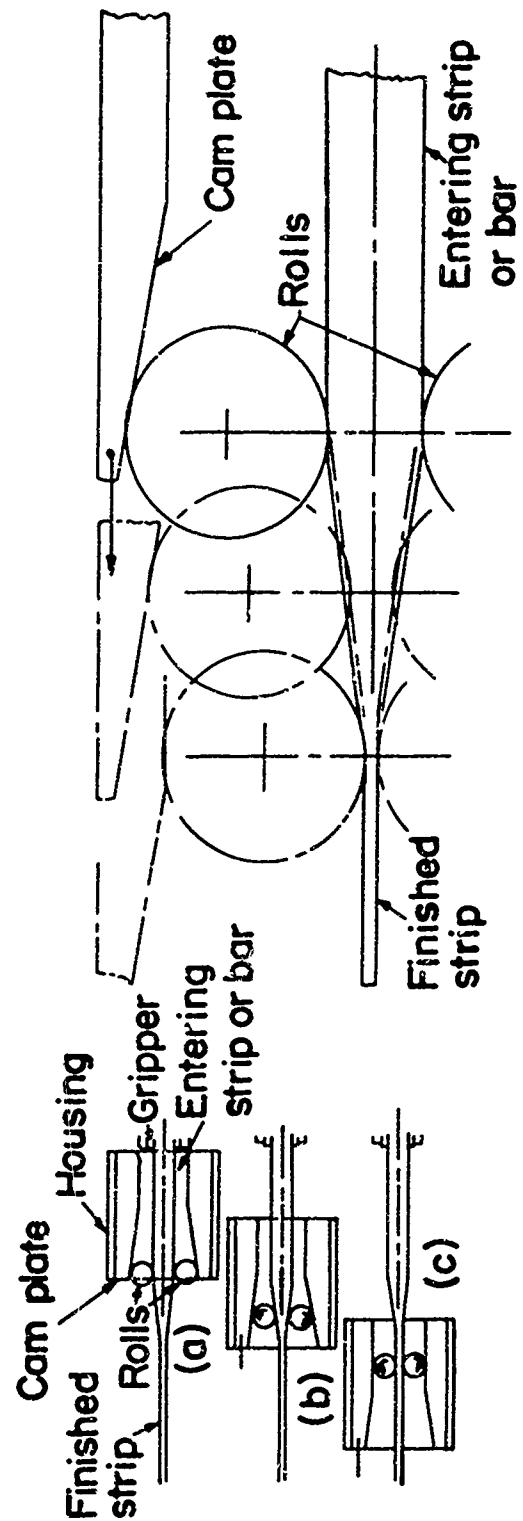
Figure 9   The Krause Mill

Figure 10

Heat Treating of Steel
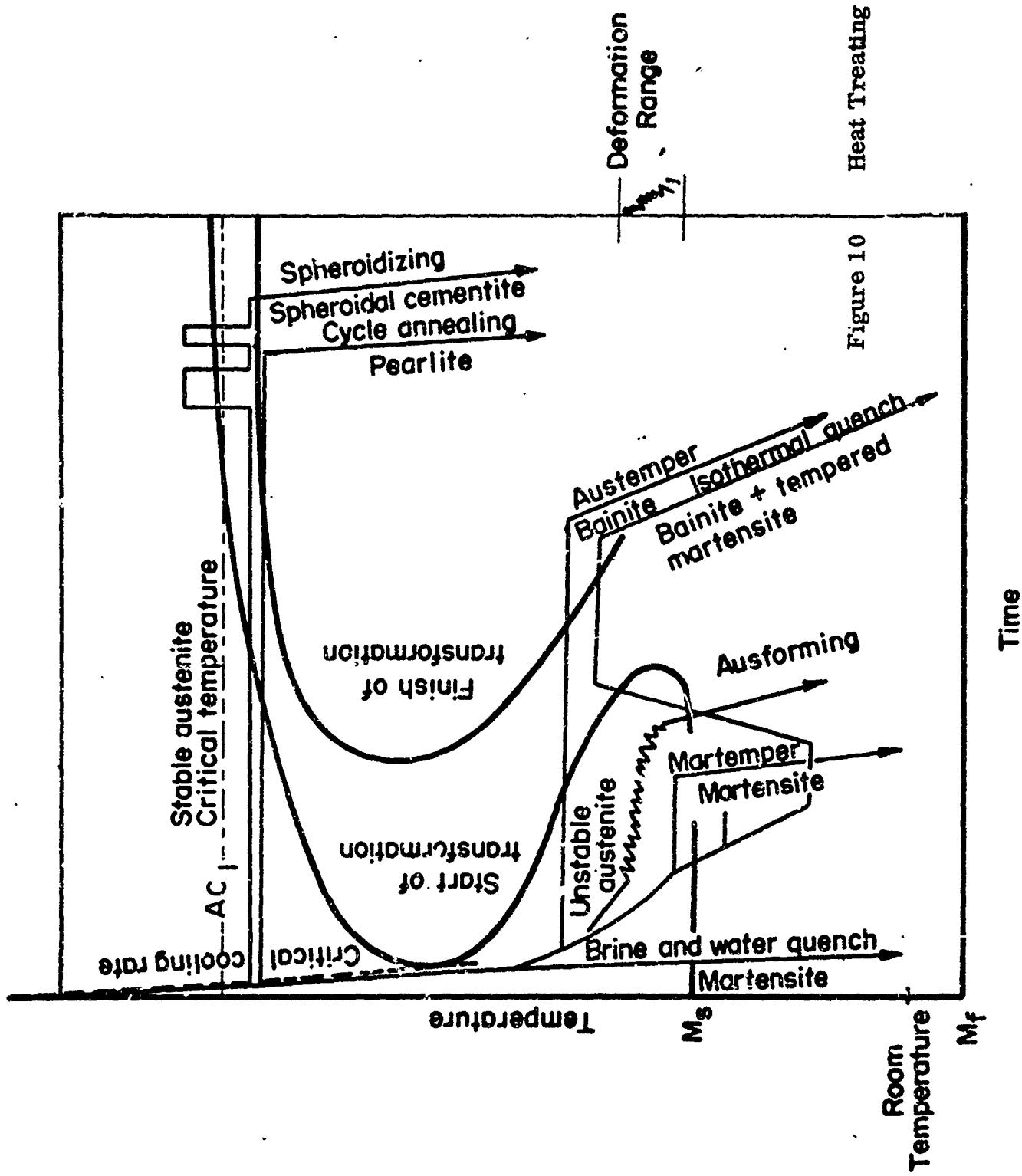
COLADA CONTINUA DE ALUMINIO

por Juan Luis Ciarlo y Roland Meillat

Introducción

En el presente trabajo hemos buscado mostrar, en forma concreta, el actual proceso de fabricación de Cables de aluminio-acero y almelec puesto a punto en CAMEA S.A. en sus modernas instalaciones de Villa Lugano - Capital Federal.

Teniendo en cuenta que la etapa más importante del proceso la constituyen la colada y laminado de la barra para obtener el alambrón de $\emptyset$ 9 ^{5} mm, se han desarrollado ambas operaciones en detalle, en tanto que las res' tes de trefilado y cableado se mencionan a título complementario, dado que no d ren en líneas generales, de lo tradicional.

En lo fundamental, el proceso se basa en el denominado sistema Properzi.

Los primeros resultados obtenidos por Hilario PROPERZI en la colada y laminado de alambre de Pb (PF 327ºC) condujeron a ensayar, con éxito, el mismo sistema para el zinc (PF 420ºC) para pasar luego al Aluminio (PF 658ºC).

Obtenido el alambrón de aluminio se buscó entonces su adaptación para la utilización en la fabricación de cables conductores.

Las ventajas que presenta este sistema al evitar el precalentamiento inter medio de placas o barrotes antes del laminado o prensado, y la utilización de materiales y equipos mucho más livianos y veloces, con un menor costo de producción, habían despertado anteriormente el interés de varios investigadores.

Ya en 1858 Henry Bessemer proponía la colada directa del acero entre cilindros refrigerados, aunque lamentablemente con resultados poco alentadores.

Para el caso particular del aluminio merecen citarse:

* Máquina Hazelett - Para la obtención de bandas laminadas. La colada se efectúa entre dos cintas metálicas sin fin, paralelas y refrigeradas exteriormente por agua.

* <u>Máquina Hunter Douglas</u> - Similar a la anterior, para la obtención de bandas, presenta como diferencia el reemplazo de las cintas por cadenas de elementos de lingoteras articuladas refrigeradas individualmente por refrigeración con agua.

* <u>Máquina Properzi</u> - Para la obtención de alambrón. El metal es colado en la garganta tallada en una rueda de cobre refrigerada interiormente y cerrada a 180° por una cinta de acero enfriada exteriormente por agua.

Las 3 máquinas tienen como puntos comunes fundamentales los siguientes:

1. No existe desplazamiento relativo entre el metal en curso de solidificación y el molde.

2. El molde está completamente cerrado en toda su longitud.

3. El contacto entre el metal colado y el elemento refrigerado del molde se efectúa sobre una superficie relativamente importante. Por lo tanto las posibilidades de regular la refrigeración son amplias.

Los puntos enunciados permiten obtener un buen estado de superficie del producto colado y al no existir desplazamiento relativo metal-molde, se evitan los esfuerzos mecánicos sobre el metal en curso de solidificación, que pueden ser eventuales causas de fisuras o roturas, altamente nocivas para la transformación posterior.

Si bien luego de pacientes esfuerzos logróse obtener un alambrón íntegro (libre de fisuras y sopladuras), quedaba aún por resolver el problema metalúrgico que planteaba la calidad exigida para la utilización en el campo de la energía eléctrica.

Como veremos más adelante, la cuestión ha sido oportunamente resuelta y actualmente resulta posible -mediante el control y la regulación adecuada de las variables correspondientes- obtener una calidad que responde ampliamente a las exigencias de las normas internacionales.

Si bien este modernísimo proceso es conocido en algunos países del mundo, su presencia en nuestro país abre posibilidades insospechadas en cuanto a tonelaje y precios de alambre de aluminio o aleación.

Digamos que, al 31/8/64, CAMEA S.A. ha fabricado desde la puesta a punto del proceso -en 1963- más de 3.000 Km de cables de diversos tipos, equivalentes a un tonelaje global del orden de las 700 Tn y continúa con su programa de producción a fin de aprovisionar no sólo el mercado local sino la exportación hacia otros países del continente, en particular Brasil y Chile.

A continuación detallaremos nuestro proceso de fabricación que, en sus

grandes líneas responde al utilizado habitualmente en las usinas Pechinev en Fran
cia, con las lógicas adaptaciones de una puesta a punto local, que permite igual-
mente mantener el standard de calidad que asegura al utilizador nacional y extran
jero la regularidad de las características exigidas para este tipo de materiales.

ASPECTOS TECNOLOGICOS DEL PROCESO

Tanto la elaboración del cable aluminio-acero como la del cable almelec
se efectúan en las mismas instalaciones. Para el caso del Almelec se utilizan
además dos hornos adicionales de tratamiento térmico (temple y revenido) indis
pensables para esta fabricación.

En el apéndice se incluyen las fichas técnicas de cada máquina con sus co-
rrespondientes producciones horarias aproximadas.

FUSION

CAMEA S.A. cuenta para esta operación con modernos Hornos Gautschi de
fusión, a gas natural, de 7 Tn de capacidad, equipados con 3 quemadores solidarios
que totalizan un caudal horario del orden de los 200 m3/h. La marcha de los que-
madores se regula automáticamente por un sistema de seguridad y la disposición
estratégica de pirómetros de bóveda y de baño.

Por razones de calidad, como veremos más adelante, la composición de
carga se efectúa preferentemente con 100% de metal nuevo - lingotes de A5C (alu-
minio conductor); Mg metálico y aleación madre AS 33 (aluminio-silicio 33%) para
el caso del almelec.

La utilización preferente de lingotes de 1a. fusión permite, además de ase
gurar la regularidad y constancia de la composición química, reducir el ciclo d,
horno aumentando la velocidad de fusión, que puede estimarse en el orden de 2 Tn/h.

Completada la fusión se efectúa en el mismo horno el "tratamiento al flux"
tendiente a eliminar las impurezas nocivas tales como el Titanio y el Vanadio, que
inciden en forma importante sobre el aumento de la resistividad.

En cuanto al contenido de las demás impurezas, los valores máximos están
asegurados por la calidad del aluminio de base y las precauciones que se toman ten
dientes a evitar la contaminación del metal en curso de transformación. Las tem-
peraturas de fusión oscilan, según los casos entre 720 y 780ºC.

COLADA - LAMINADO

Ambas etapas se desarrollan simultáneamente mediante una sincronización adecuada de las instalaciones utilizadas. Ellas son:

* Horno Gautschi Eléctrico

De capacidad similar al horno de fusión de gas (7 Tn), éste es en cambio calentado por una serie de resistencias eléctricas colocadas convenientemente en la bóveda del mismo.

El consumo es del orden de los 80 Kwh y el calentamiento regulable sistemáticamente por pirómetros, ubicados en la bóveda y en el baño de metal líquido. Al igual que el horno de fusión es basculante a ambos lados por medio de un pistón hidráulico ubicado bajo el piso del mismo. Su peso es del orden de las 35 Tn.

El metal.llega a través de una canaleta de transvase portatil, a la que es volcado haciendo bascular el horno de fusión.

El tiempo de transvase de 7 Tn es del orden de los 18 minutos.

En función del tipo de cable a fabricar (alu-acero o almelec) se mantiene el metal en el horno de colada hasta obtener la temperatura adecuada para cada tipo de material.

Resulta útil destacar que las características mecánicas y eléctricas exigidas para el alambre a diámetro final están, en el caso del cable alu-acero, íntimamente ligadas a las condiciones de colada y laminado de la barra, dado que la posterior transformación en frío (trefilado) se efectúa sin ningún tratamiento térmico adicional.

En el caso del almelec, las razones que rigen los parámetros de la colada obedecen fundamentalmente a la necesidad de obtener una barra sana en virtud de que, comparativamente con el aluminio, las aleaciones al Si Mg 2 presentan una mayor tendencia a fisurarse en caliente.

* Máquina de Colada Tipo Properzi

Si bien difiere ligeramente en sus dimensiones y aspecto exterior a la original Properzi, conserva en cambio sus características principales.

Está constituída por una rueda de colada, un recipiente o tanque intermedio entre el horno y la rueda, y un sistema de refrigeración interior y exterior de la misma.

* Tanque intermedio

Se halla solidario con la rueda de colada, y ofrece la posibilidad de ser desplazado convenientemente hacia adelante o atrás para permitir la posición adecuada de la boquilla de colada en la garganta de la rueda. En nuestro caso la capacidad del tanque es del orden de ∿ 15 lts (40 Kg).

Su misión es la de mantener un nivel suficiente de metal que asegure una vena líquida regular y constante durante toda la colada.

El metal llega al tanque, construído en fundición de hierro, por medio de una canaleta ubicada debajo del pico de descarga del horno. Un mechero a gas permite aplicar un calentamiento contínuo o intermitente a fin de mantener la temperatura del metal dentro de los límites pre-establecidos para cada caso.

En la pared situada al costado de la rueda se halla el orificio de salida donde se coloca la boquilla de colada, constituída en nuestro caso por un tubo acodado de dos piezas de fundición de hierro, cuya misión consiste en conducir la vena líquida hacia la garganta de la rueda.

A fin de mantener una colada "tranquila", sin turbulencias ni interrupciones de la vena líquida, es necesario mantener el extremo inferior de la boquilla levemente sumergido (∿ 5mm) bajo el nivel del metal dentro de la garganta de la rueda. Ello se consigue accionando convenientemente el tapón cónico situado en el extremo anterior de la boquilla (dentro del tanque) por medio de un sencillo mecanismo de avance-retroceso; manejado por el mismo operario colador que regula de este modo el caudal de metal a enviar a la rueda en movimiento.

Teniendo en cuenta que el aluminio líquido disuelve el hierro de los elementos en su contacto, es necesario aplicar una pintura de protección a la canaleta, al tanque y a la ! boquilla de colada.

En el caso particular de esta última, la operación reviste cierto cuidado dado que la regularidad de la vena líquida está condicionada a una superficie interior de la boquilla perfectamente lisa, libre de granos o porosidades que puedan producir turbulencias o el ataque rápido de la misma, con los siguientes inconvenientes.

Al igual que en la colada continua o semicontinua de placas y barrotes es necesario mantener el metal en movimiento por debajo de su piel de alúmina que lo cubre (colada en manantial) para evitar el entrañamiento de la misma película al romperse y de burbujas de aire que desmejoran la calidad del producto colado y originan inconvenientes durante la transformación posterior.

* Rueda de colada

Está constituída por un anillo de cobre montado sobre dos discos de fundición de hierro refrigerados por dentro y accionados por un motor que le confiere un movimiento de rotación sobre su eje central.

En el anillo de cobre se ha tallado una garganta de sección trapezoidal de ∿ 1000 mm2. La mitad de la garganta permanece cerrada por medio de una cinta de acero de bajo carbono, tendida en el borde opuesto por una po lea loca del mismo diámetro de la rueda.

La tensión de cierre de la cinta de acero se logra mediante un tornillo sin fin.

La Lingotera está constituída entonces por el sector de la garganta cerrado por la cinta y dada su extensión relativamente importante y la refrigeración exterior aplicada sobre la cinta a partir del contacto con el metal lí quido, es posible regular con cierta amplitud la velocidad de solidificación a fin de obtener una barra íntegra y suficientemente plástica para favorecer la transformación inmediata en el laminador.

La velocidad de giro de la rueda es regulable oscilando alrededor de 3 rpm, lo que equivale a aproximadamente 10 mts de barra en ese lapso.

Si se tiene en cuenta que 1 mt de la barra pesa alrededor de 2,5 kg veremos que la producción horaria de la rueda oscila en los 1500 kg/h, lo que significa un ritmo de producción elevado además de otras ventajas, en comparación con los valores alcanzables por los métodos tradicionales, a los cuales es necesario agregar el precalentamiento del barrote o lingote a transformar; los recocidos intermedios, la limitación en el largo del alambrón a obtener y la utilización de máquinas y elementos de mayor volu men y peso.

A título ilustrativo digamos que para el caso de una colada de 7 Tn (que aún puede ser alimentada periódicamente en curso) se puede obtener un alambrón laminado a 9,5 mm de diámetro, cuyo peso es de ∿ 200 gr/mt, con un largo de 35 Km, sin cortes, en menos de cinco horas.

LAMINADOR SPIDEM

Presenta diferencias importantes con relación al original Properzi. En tanto que este último consta de 13 cajas de cilindros cruzadas y las secciones pasan consecutivamente de la forma triangular a la hexagonal, para terminar en sec

ción circular del alambrón, el Laminador SPIDEM presenta 8 cajas de cilindros también cruzadas y la sección de la barra pasa alternativamente de la forma oval a la circular terminando en ésta con el mismo diámetro final de 9, 5 mm.

Las reducciones de sección entre cajas oscilan entre 20 y 30%, exceptuando la primera caja en la que se aplica una reducción del orden del 60% aprovechando la temperatura de entrada de la barra que es de alrededor de 450°C.

La sección de la barra a la entrada es de ∿ 1000 mm2 y luego de los 8 laminados sucesivos se obtiene el alambrón cuya sección es de ∿ 70 mm2. Las velocidades de entrada y salida son respectivamente 10 y 120 mt/min aproximadamente, lo que equivale como hemos visto a ∿ 1500 kg/h.

La relación de velocidad de una caja a otra es fija, y se modifica gradualmente la velocidad del conjunto accionando sobre el control de un tablero ubicado cerca del operario colador.

De tal modo resulta posible sincronizar la velocidad del laminador con la rueda de colada.

Como elementos complementarios del laminador merecen citarse:

* Horquilla contrapeso

Consiste en un juego de 2 rodillos contrapesados que se deslizan en forma vertical en una columna ubicada a distancia intermedia entre la rueda y el laminador.

Su misión es la de permitir la formación de un bucle en la barra, lo que facilita la sincronización gradual de las velocidades del conjunto rueda-laminador.

Como se verá luego, las variaciones de velocidad obedecen primeramente a la puesta en marcha y luego, al hecho de obtener obligatoriamente un determinado valor de resistencia a la tracción sobre el alambrón a 9, 5 mm (en el caso del aluminio-acero) que permita luego del trefilado a diferentes diámetros finales del alambre de aluminio, mantener las características, mecánicas dentro de los valores exigidos por las normas.

Tales variaciones resultan además función de las temperaturas del metal, en la rueda y durante su paso a través de las 8 cajas de cilindros del laminador.

A continuación de la horquilla contrapeso se ha ubicado una guillotina neumática que permite efectuar en forma rápida el corte o despunte de la barra antes de proceder a la introducción en los rodillos guía situados a la entrada de la 1a. caja del laminador.

* Trompa de salida y envolvedor

Inmediatamente a la salida de la última caja y sobre la pared posterior del laminador se ha colocado en nuestro caso un caño de latón en forma de S (Ø 50 mm - largo 9 mts), también contrapesado cuya misión es la de dirigir el alambrón que sale a 120 mts/min, con una temperatura, comprendida entre 200 y 280ºC, según los casos, hacia el envolvedor.

Este está constituído por un tonel formado por varios listones de madera dura dispuestos en forma circular y unidos entre sí por medio de 2 anillos exteriores de hierro, y se halla colocado sobre un chassis cuadrado montado sobre 4 ruedas locas.

El conjunto envolvedor-chassis se coloca inmediatamente debajo de la trompa de salida del laminador. Al iniciar la colada, el primer extremo del alambrón se dirige rápidamente hacia el borde interior del envolvedor produciéndose automáticamente el enrollado del alambrón sobre sí mismo.

El contrapeso situado en la zona media de la trompa facilita el fácil manejo de un extremo posterior, el que es acompañado por el operario a fin de obtener una bobina compacta cuyo peso total oscila en los 600 kg (∿ 12.000mts).

Mediante un segundo envolvedor colocado igualmente sobre un chassis con cuatro ruedas locas, se desplaza, en el momento oportuno, el envolvedor lleno reemplazándolo por el vacío acompañado con un golpe de mano enguantada, el alambrón hacia este último. Luego se corta con una tijera al efecto el tramo de alambrón que une ambos envolvedores, se retira del chassis el esqueleto del envolvedor lleno por medio de un pequeño guinche y se extrae la bobina con la ayuda de un tow-motor que la conduce hasta la balanza y posterior al stock.

* Circuito de lubricación - refrigeración

El laminador SPIDEM dadas sus características particulares está equipado con un circuito de lubricación-refrigeración atento a la misión que debe cumplir el aceite de laminado que se utiliza.

Además se cuenta con un circuito de lubricación de cojinetes y mecanismos que si bien cumple una misión importante no incide sobre las características del metal a obtener.

Por el contrario, el aceite de laminado reviste una función fundamental al actuar en 2 sentidos:

1.   Como lubricante propiamente dicho, evitando el "pegado" del metal al cilindro durante el laminado de la barra. Es sabido que una lubri

cación deficiente trae como consecuencia un fenómeno de adheren-
cia o pegado de metal a los cilindros de laminado, metal que vuelve
a depositarse luego sobre el mismo alambrón produciéndose sobre
la superficie de éste el defecto denominado "escamas" o "pajuelas"
sumamente perjudicial en las etapas posteriores y al estado final
dado que resulta prácticamente imposible eliminarlo afectando no
sólo el estado de superficie del alambre terminado sino también su
conductividad eléctrica.

En nuestro caso se utiliza un aceite soluble de importación en una
concentración que se verifica antes y durante cada colada y que de-
be mantenerse lo más próxima posible al 20 º/oo.

2. Como refrigerante, al ser proyectado a una cierta presión, caudal
y temperatura sobre los cilindros durante el laminado.

La regulación adecuada de las 3 variables, que está a su vez ligada
a la temperatura de la barra y a la velocidad del laminador permite
aplicar una velocidad de enfriamiento, que resulta función de las 5
variables mencionadas, y cuya consecuencia se traduce en un deter-
minado valor de Rt a obtener sobre el alambrón laminado. Este va-
lor de Rt para una composición química determinada, es entonces
función del grado de deformación en frío aplicada.

A los efectos de regular más fácilmente la velocidad de enfriamien-
to, cada caja de cilindros ofrece la posibilidad de modificar inme-
diatamente el caudal de lubricante por medio de un robinete.

La capacidad de la cuba de aceite soluble, siendo del orden de los
1500 lts asegura un caudal constante de aceite, el que a su vez de-
be ser mantenido a una temperatura lo más constante posible (± 5ºC)
según se trate de A5C (50ºC) o Almelec (60ºC).

El aceite es reciclado por medio de bombas que lo dirigen desde la
cuba hacia los picos situados frente a c/caja de cilindros. De allí,
pasa a un colector ubicado en el piso del laminador que lo conduce
nuevamente a la cuba pasando previamente por un filtro de papel es-
pecial que retiene las virutas de aluminio y las impurezas que reco-
ge durante el laminado.

A fin de regular la temperatura se dispone de un tanque intermedio
con termostato que permite calentar o enfriar el aceite, según las
necesidades, por medio de una serie de resistencias eléctricas y
una serpentina donde circula agua fría respectivamente.

La presión del aceite en trabajo es de ~ 0,5 a 0,8 kg/cm2.

El consumo por tonelada laminada es del orden de 2,5 lts/Tn inclu-
yendo las pérdidas por evaporación.

El equipo obrero afectado al funcionamiento del conjunto Horno de colada-
rueda-laminador, está constituído por 3 obreros bajo la responsabilidad del
operario colador quien, en acuerdo con el capataz de la sección, modifica
las velocidades del conjunto según las necesidades. Los 2 obreros restan-
tes una vez puesta en marcha la colada atienden la operación de enrollado
y evacuación de las bobinas.

El control de las características mecánicas de c/rollo en el caso del A5C es efectuado por un agente del Servicio de Control asistido por el mismo capataz de la sección.

TREFILADO

La fabricación de cables alu-acero y de almelec presentan en común la utilización de una moderna máquina trefiladora de 9 trefilas fabricada por OTT (Office Technique des Tréfilés).

En el caso particular del almelec se utiliza una trefiladora Robertson adicional para efectuar el primer desgrosado exigido por razones metalúrgicas que imponen un temple y madurado a un diámetro intermedio, que corresponde dentro de ciertos límites a dos veces y media el diámetro final del alambre a cablear.

Para el alambre de aluminio se procede en una sola etapa sobre la trefiladora OTT. La bobina proveniente del laminador SPIDEM, previamente enfriada al aire, es colocada en el costado de entrada de la OTT y enhebrada a través de las trefilas de la misma.

La elección de estas últimas está en función del diámetro final a obtener dado que el diámetro inicial (9, 5mm para Alu y 6, 25mm para Almelec) se mantiene sensiblemente constante.

Al igual que en las cajas de cilindros del laminador Spidem, la trefiladora OTT permite la regulación de la velocidad de trefilado en forma individual para cada trafila por medio de un tambor envolvedor de arrastre, refrigerado interiormente por circulación de agua facilitando de tal modo:

a) el sincronizado de la marcha en conjunto
b) el enfriamiento del metal en curso de transformación
c) el trefilado sin deslizamiento relativo entre el alambre y el tambor de arrastre

Teniendo en cuenta que el diámetro final del alambre puede oscilar entre ámbitos relativamente importantes (4, 86mm a 1, 90 mm en nuestro caso), la elección de las trafilas se hace buscando aplicar una reducción por sección, que generalmente resulta del orden del 30% promedio, para cada pasada.

Antes de completar el trefilado de la 1a. bobina se procede a soldar a tope, mediante una sencilla operación con pasaje de corriente eléctrica, el extremo final de esa bobina con el inicial de la siguiente. Ello asegura una continuidad de fabricación que permite alcanzar una producción horaria de 100 a 900 kg/h en función del diámetro de salida.

A la salida de la trefiladora el alambre es enrollado en bobinas de 40 a 50 kg de capacidad que son utilizadas posteriormente en la operación de cableado.

El manejo, carga y descarga de la trefiladora OTT queda a cargo de un so lo operario, quien a su vez es responsable de la identificación del material y de efectuar las anotaciones correspondientes.

A título complementario podemos agregar que la Trefiladora OTT ha sido puesta en servicio a mediados de 1963 habiendo producido hasta el 31/8/64 aproxi madamente 1000 Tn de alambres de distintos tipos, para usos diversos.

Como instalaciones complementarias de la operación de trefilado pueden mencionarse además de la trefiladora Robertson, los siguientes hornos de trata miento térmico, utilizados únicamente en la fabricación de Cables Almelec.

* Horno CL

Fabricado por la firma Gautschi, de Suiza, específicamente para el templa do y envejecido de productos extrudados (perfiles, barras, etc.) ha sido puesto a punto con éxito para el templado y madurado de rollos de alambre de almelec de diámetro 6, 25 mm - de ∿ 250 kg c/u.

Templado

Esta operación, para ser efectiva requiere un tiempo de maniobra corto para asegurar el solubilizado del siliciuro de magnesio pre- viamente puesto en solución mediante un mantenimiento mínimo de 20 minutos a 560ºC, seguido de un enfriamiento brusco en agua a tem peratura ambiente.

La calefacción del horno está asegurada por dos quemadores a gas de 40 m3/h de caudal c/u, colocados simétricamente en los extremos opuestos del horno cuyas dimensiones útiles aproximadas son: lar go 7 mts, ancho 1 mt y alto 1, 3 mts.

La carga total de los rollos, del orden de 2, 5 Tn - 10 rollos - se coloca previamente en un bote (construído en caños de hierro) que es introducido y sacado del horno con ayuda del puente grúa de la sec ción.

Para la operación de temple se dispone de una cuba con agua fría en circulación cuyo volumen útil alcanza aproximadamente a 15000 litros.

Al igual que los restantes hornos a gas, el CL está equipado con un seguro sistema de alarma que corta automáticamente la llegada de gas a los quemadores en el caso de producirse una anomalía en el funcionamiento del mismo.

El manejo es sumamente sencillo y el control y regulación de tem- peratura se efectúan por medio de 2 pirómetros ubicados convenien temente.

Un registrador MEC1 permite obtener en cada instante un gráfico

de la temperatura del interior del horno, que es sensiblemente regular y constante en todos los puntos del mismo.

Ello resulta particularmente importante para no "quemar" metal por un sobrecalentamiento, asegurando por otra parte la puesta en solución cuantitativa del Si Mg 2 íntimamente ligada a la temperatura crítica del temple.

Madurado

En el mismo horno CL se efectúa el tratamiento complementario de madurado artificial (10 hs a 100ºC).

El objeto de este tratamiento particular, al acelerar el madurado natural que se efectúa a temperatura ambiente durante algunos días, es el de obtener además una repartición más homogénea de los constituyentes precipitados, lo que garantiza una mayor regularidad en las características mecánicas a obtener al estado final.

La misma carga de la operación anterior (templado) vuelve a ser introducida en el horno durante 10 hs a 100ºC $\pm$ 5ºC para producir. la precipitación del Si Mg 2 previamente solubilizado.

La fácil regulación del horno, su buena inercia térmica y la gran estabilidad y regularidad de temperatura en toda la superficie del horno permiten efectuar los tratamientos de templado y madurado artificial sin inconvenientes.

La producción horaria para ambos tratamientos es del orden de 250 kg/h.

* Horno SL

Al igual que el CL se lo utiliza únicamente en el proceso de fabricación del cable almelec.

Las características de este tipo de horno, tales como

- Calefacción por tubos radiantes sobre las paredes laterales
- Facil regulación de marcha
- Estabilidad y repartición homogénea de la temperatura interior

lo hacen perfectamente adaptable para el tratamiento de revenido final del alambre.

La finalidad de este tratamiento de 12 a 15 hs a 160ºC $\pm$ 5ºC es la de completar la eliminación del Si Mg de la solución sólida, disminuyendo de tal modo la resistividad por debajo de 3,25 μ Ω cm2. cm, y actual además sobre las características mecánicas, en particular el A% $\geqslant$ 3 manteniendo una Rt $\geqslant$ 30 kg/mm2, valores todos ellos exigidos por las Normas Interna_ cionales de Cables Conductores.

La producción horaria oscila en los 150-200 kg/h para cargas de $\sim$ 2 Tn.

CABLEADO

CAMEA S.A. cuenta en su planta de fabricación de cables con dos máquinas cableadoras que ofrecen la posibilidad de fabricar cables con o sin alma de acero, protegida o nó esta última y con una cantidad de alambres o hilos que abarca la gama comprendida entre 3 y 127 hilos.

En los cuadros que figuran en anexo se consignan las características de los cables fabricados hasta el momento sobre pedido de clientes.

En las fichas técnicas correspondientes se acompañan las características de cada cableadora con indicación de la capacidad de producción promedio en función del diámetro de los alambres a cablear.

Ambas cableadoras CB 1 y CB 2 son atendidas por un operario responsable y un ayudante.

La velocidad de cableado puede oscilar entre 10 y 50 mts/min.

Teniendo en cuenta que nuestras cableadoras no difieren de lo tradicional en este tipo de máquinas, no nos extenderemos sobre el tema.

Digamos solamente que la producción de cables Alu-Acero y Alemelec al 31/8/64 en función de la demanda, ha sido la siguiente:

	Km	Tn
Aluminio-Acero	1.814,7	354,5
Almelec	1.231,7	301,0
Total	3.046,4	655,5

La capacidad de producción actual de la Sección Cableado puede sobrepasar las 150 Tn/mensuales según el tipo de cable a fabricar.

CONSIDERACIONES METALURGICAS

Aún teniendo en cuenta que el objeto de este trabajo es puramente tecnológico estimamos necesario efectuar algunas consideraciones de orden metalúrgico dado que se imponen al proceso de fabricación ciertas limitaciones a respetar y cuya justificación, como es lógico resulta evidente.

Según normas internacionales se exige a la vez, para un mismo diámetro de alambre, un valor mínimo de carga de rotura, una resistividad máxima y una capacidad de deformación caracterizada, ya sea por el porcentaje de alargamiento o por el número de plegados sobre sí mismo.

Se ha constatado que tales características están íntimamente ligadas a la composición química, a las condiciones de colada y laminado y al grado de deformación en frío aplicado. Por ej.: para una misma composición química, lo que incide favorablemente sobre la conductividad, actúa en forma contraria sobre las características mecánicas y vice-versa.

El estudio de las siguientes variables, efectuado por varios investigadores, ha permitido observar su influencia y resolver la cuestión.

1. __Composición Química__

   a) __Caso del Aluminio Conductor (A5C)__

   Inciden en forma importante el tenor de impurezas presentes, destacándose algunas de ellas como muy nocivas aún en valores bajos, tales como el Ti ($\leqslant$ 0,004%) y el Vanadio ($\leqslant$ 0,001%).

   El gráfico en anexo muestra la influencia de cada impureza sobre la resistividad del alambre a un mismo diámetro final - es decir idénticas condiciones de transformación.

   Se destaca netamente que impurezas tales como el V Ti y Mn son altamente perjudiciales en tenores aún inferiores a 0,01.

   Las 2 primeras (V y Ti) son eliminadas mediante un tratamiento con un flux especial que favorece la formación de compuestos que se eliminan parcialmente quedando el resto bajo forma de constituyentes fuera de la solución sólida que por lo tanto no perturban la transmisión de corriente eléctrica. El tenor residual después del tratamiento es del orden de V $\leqslant$ 0,001% y Ti $\leqslant$ 0,004. Es de destacar que el V se encuentra a menudo en tenores prácticamente despreciables, aún antes del tratamiento al flux y el Mn no excede habitualmente los límites perjudiciales.

   Los gráficos de dispersión que figuran en anexo muestran los valores de los productos CAMEA S.A. - que se hallan encuadrados dentro de las siguientes tolerancias fijadas para esta fabricación

Cu	Mg	Mn	Fe	Si	Ti	Zn
$\leqslant$ 0,008	$\leqslant$ 0,008	$\leqslant$ 0,006	0,20$\pm$0,02	0,07$\pm$0,01	$\leqslant$ 0,004	-

Digamos al pasar que el control de composición química se efectúa obligatoriamente (al igual de Rt y A%) a diámetro 9,5 durante la colada y laminado de cada rollo.

CAMEA S. A. posee un espectrolector CAMECA de lectura directa que permite conocer la composición química (7 elementos) de un material en menos de 5 minutos transcurridos entre la extracción de la probeta -en el tanque intermedio de la rueda de colada y la expresión de los resultados obtenidos sobre el espectrolector.

Con los valores indicados y una $Rt \geqslant 17$ kg/mm2, se está en condiciones de garantizar una $\rho \leqslant 2,8264 \, \mu\Omega$ cm2 . cm (CEI).

b)   <u>Caso del Almelec</u>

Al igual que para el A5C, los valores del gráfico de dispersión se hallan comprendidos dentro de los siguientes límites, fijados como máximos para garantizar una $Rt \geqslant 33$ kg/mm y una $\rho \leqslant 3,28 \, \mu\Omega$ cm2 x cm exigidas por las Normas Internacionales.

Cu	Mg	Mn	Fe	Si	Ti	Zn
$\leqslant$ 0,008	0,7 $\pm$ 0,1	$\leqslant$ 0,006	0,2 - 0,3	0,5 - 0,7	$\leqslant$ 0,004	-

2.   <u>Condiciones de Colada y Laminado</u>

a)   <u>Caso del Aluminio Conductor A5C</u>

Investigaciones anteriores han puesto en evidencia que las condiciones de colada, en particular la velocidad de enfriamiento, ejercían una influencia importante sobre la conductividad cuando se mantienen constantes las restantes variables.

Comparativamente con alambres obtenidos por el sistema clásico de prensado (o laminado) y trefilado, el alambre fabricado por el sistema PROPERZI presenta un valor de resistividad mayor. Además se constató que la repartición de constituyentes era mucho más fina en el proceso clásico que en el PROPERZI.

Varias explicaciones han sido dadas por diferentes autores. A continuación se resume la enunciada por el Ing. CHEVIGNY - Jefe del Servicio de Investigaciones de PECHINEY en Chambery:

"Tanto en los barrotes cuadrados (sección 10.000 mm2) como en la barra SPIDEM (sección 1.000 mm2) la velocidad de solidificación

serfa tal que determinarfa segregaciones menores de las impurezas
principales Fe y Si. Estas constituirían en la proximidad de los lf-
mites de las dendritas, zonas de baja conductividad, aislando en ma_
yor o menor grado las dendritas entre sf.

En el caso de los barrotes cuadrados, varios factores favorecerían
su destrucción, al menos parcial, tales como el precalentamiento a
450-500ºC previo al laminado que favorecería la difusión de las im-
purezas y producirfa un cierto efecto de homogeneizado, y además
el % de deformación elevado - correspondiente a la transformación
de una sección de 10.000 mm2 dispersarfa suficientemente las se-
gregaciones para que éstas no tuvieran efecto importante sobre la
conductividad.

Por el contrario, en la barra Properzi, el efecto de homogenei za-
ción no tendría tiempo de manifestarse dada la sucesión rápida de
las operaciones. Además el grado de deformación, mucho menor
que para los barrotes cuadrados no conducirfa a una dispersión muy
profunda. Con respecto a este último, un aumento en la sección de
la barra Properzi, cuya consecuencia es un aumento del % de reduc_
ción posterior, mejora sensiblemente la conductividad del alambre.
Por otra parte, un homogeneizado de los barrotes a 500ºC mejora
sensiblemente la conductividad, pero por razones obvias no se tra-
ta de efectuar un homogeneizado de la barra Properzi".

El problema fue resuelto prestando atención a las condiciones de co_
lada y laminado y respetando las limitaciones en cuanto a composición quí-
mica se refiere.

Se destaca que un recocir) intermedio del alambrón mejora, para
una misma composición química, la conductividad del alambre a diámetro
final.

Resulta necesario destacar además que regulando convenientemente
las condiciones de colada y laminado, se ha logrado evitar el recocido inter_
medio del alambrón pudiendo obtenerse no obstante las características me-
cánicas y eléctricas exigidas, como lo muestran los valores que figuran en
el anexo.

Teniendo en cuenta que el diámetro de salida del alambrón se man-
tiene constante a 9,5 mm y que el diámetro final puede variar dentro de ám_
bitos importantes se debe prever una marcha del conjunto rueda-laminador
tal que, a cada diámetro final corresponda una Rt a ∅ 9,5 que permita la
transformación en frfo necesaria para alcanzar la Rt final sin excederse
dado que a una mayor Rt corresponde consecuentemente una mayor resisti_
vidad.

Mediante el cálculo teórico y la confirmación práctica se han logra-
do establecer los límites de Rt a ∅ 9,5 mm en cada caso particular, los que

son controlados obligatoriamente al comienzo de cada rollo en curso de fa
bricación por medio de una máquina de tracción Amsler de 2 Tn -en nuestro
caso- colocada a la salida de la trompa del laminador.

b)   Caso del Almelec

Dado que esta fabricación contempla un tratamiento de temple y ma
durado a aproximadamente dos veces y media el diámetro final, la marcha
del conjunto rueda-laminador se rige por la necesidad de obtener una barra
sana pues como ya hemos dicho anteriormente, las aleaciones al silicio de
magnesio presentan, comparativamente con el aluminio, una mayor tenden
cia a fisurarse en caliente.

Analizadas las dos variables fundamentales sólo resta indicar que
la última de ellas, la resistividad es función de aquellas.

En el caso particular del almelec no debe olvidarse que las caracte
rísticas mecánicas y eléctricas se obtienen por medio de un tratamiento
térmico de revenido. Ello significa un control delicado de la evolución de
tales características en curso de tratamiento para asegurar una calidad
dentro de normas.

Un sencillo procedimiento mediante el empleo de "probetas piloto"
nos ha permitido solucionar el problema satisfactoriamente.

CONCLUSION

Con el presente trabajo no pretendemos haber efectuado un nuevo aporte al
campo de la Metalurgia de transformación del aluminio y de la aleación aluminio-
siliciuro de magnesio destinados a la fabricación de cables conductores.

Nos hemos limitado solamente a exponer los métodos de fabricación em-
pleados por una empresa local, con garantía de la calidad obtenida, comparable
con la del material de importación.

El proceso enunciado no pretende ser exclusivo ni mucho menos, sólo as-
pira a poner en evidencia el nivel alcanzado en este Campo de la Metalurgia de
Transformación en nuestro país. Ello ha sido posible merced a la gran facilidad
del operario argentino para adaptarse a nuevas tareas y el sentido de responsabi
lidad que puede evidenciar cuando le es requerida su colaboración.

El actual déficit energético del país permite suponer un desarrollo de mer

cado relativamente importante a corto plazo si se tiene en cuenta que es el Estado el cliente de mayor importancia a través de sus organismos especializados.

Es de destacar que se ha observado una marcada tendencia hacia la utilización del almelec, hecho que por otra parte se produce también en otros países del viejo y nuevo mundo, lo que ha permitido intensificar los esfuerzos en ese sentido.

Actualmente puede considerarse que CAMEA S.A. absorbe la mayor parte del consumo local y además fabrica cables para la exportación a países latinoamericanos tales como Brasil y Chile, que se hallan también abocados a la solución de su déficit energético.

Desde el punto de vista metalúrgico digamos que la colada continua y laminado simultáneo de la barra por el sistema Properzi es una solución elegante al problema de la fabricación de alambres de aluminio o almelec destinados no solamente a la fabricación de cables sino también a otros usos diversos.

Con relación al proceso clásico de fabricación de alambres por prensado (o laminado) del barrote y posterior trefilado, presenta una serie de ventajas entre las que merecen destacarse, además de la calidad y regularidad del producto terminado, un importante aumento de la productividad dado que disminuye considerablemente los costos por reducción del personal afectado y permite la utilización de bobinas más pesadas, lo que simplifica los inconvenientes de manutención, de almacenamiento y de transporte. La supresión casi total de las soldaduras es particularmente apreciada en el caso del almelec. No obstante, se trata de una fabricación que si bien requiere una mano de obra reducida obliga a una vigilancia y control técnico bastante severo para mantener el alto nivel de calidad exigido por la clientela. Las 700 Tn fabricadas dan una prueba de ello.

Por último, no queremos finalizar nuestra exposición sin hacer público nuestro agradecimiento al Directorio de CAMEA S.A. por haber permitido su divulgación y a todo el personal que ha colaborado en la recopilación y preparación de este trabajo.

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ESTUDIO DE LA COLAMINACION DE METALES

por   J. Almagro, G. Cusminsky y C. Martínez Vidal

1.   INTRODUCCION

Desde el punto de vista metalúrgico existen dos métodos básicos para unir metales. El primero consiste en obtener por fusión esa unión ya sea del mismo metal base (soldadura por fusión), o de otro metal, o aleación de menor punto de fusión ("brazing"). Por el segundo método, se obtiene esa unión en estado sólido.

Esta unión en estado sólido toma diferentes nombres en la literatura, según el proceso seguido: unión por difusión, unión por presión hidrostática, unión por identación, unión por colaminación, etc. Podemos no obstante ordenarla y dividir la en dos grandes grupos:

a)   unión en frío: cuando la temperatura de trabajo está por debajo de la llamada temperatura de recuperación. En este caso actuaría sólo la presión.

b)   unión en caliente: cuando la temperatura de trabajo es mayor que la de recristalización. Aquí además de la presión, actúan la temperatura y el tiempo.

En la actualidad se obtienen industrialmente por estas técnicas, una variedad de materiales compuestos, que permiten aunar y aprovechar al máximo diferentes propiedades de distintos metales, con la consiguiente reducción de costos.

Si bien estos procesos entraron en su etapa industrial alrededor de 1935 y en la actualidad están bien definidos empíricamente, los mecanismos que operan en la unión no están suficientemente aclarados y varios investigadores postulan su dependencia de diferentes y contradictorios factores.

La necesidad de construir en la Comisión Nacional de Energía Atómica los elementos combustibles tipo MTR para un reactor de 5 MW, hizo que se pensara en estos métodos de unión, desarrollando las técnicas correspondientes. Para ello se eligió la colaminación, proceso en el que la presión está dada por la reducción obtenida al pasar el material entre los cilindros de una laminadora.

De esta manera se obtendría la estanqueidad y condiciones de transferencia térmica necesarias. El método consiste de cerrar totalmente el núcleo fisionable de aleación aluminio-uranio; lateralmente por un marco de aluminio, y las superficies con dos tapas de aluminio, que se colaminan con el marco y el núcleo [1].

2. COLAMINACION

2.1. Trabajos previos

En 1944 Kinzel [2] da un enfoque teórico al problema, atribuyendo las causas de la unión a la difusión. En 1956 Durst [3] atribuye las causas de unión a la aproximación de las superficies a distancias interatómicas obteniéndose fuerzas de atracción superiores a las de repulsión producidas por las fuerzas de recuperación elásticas.

Parks [4], Hoffmann y Ruge [5], Williams y Bever [6], Erdman-Jesnitzer[7], etc., efectúan trabajos sobre colaminación sin agregar nuevos conceptos a los anteriores.

En 1959 Milner comienza con sus colaboradores una sistemática que dura hasta 1962 y condensa la información en un "Review Paper" [8]. Postula, al igual que Durst, que la unión se debe a la aproximación de las dos superficies, hasta llegar a distancias atómicas.

2.2. Parámetros analizados

Al iniciar el trabajo se tuvieron presentes dos objetivos:

I) La determinación de las condiciones óptimas para obtener la colaminación en el problema concreto de elementos combustibles.

II) Procurar aclarar o entender los mecanismos que operan en ese proceso.

Nos limitaremos al punto II, indicando el estado actual de los trabajos [9-10].

Al estudiar los parámetros que se suponía tenían influencia en la unión por colaminación, se les agrupó en:

a) Condiciones de superficie en el material a unir, y
b) Condiciones de laminación (proceso empleado).

En las condiciones de superficie enumeraremos:

a_1 Contaminación superficial: i) oxidación
                                          ii) adsorción y absorción de otros gases

a_2 Endurecimiento por deformaciones previas

a_3 Rugosidad

a_4 Energía almacenada

Para las condiciones de laminación se consideraron:

b_1 Deformación, dada por la reducción en una pasada

b_2 Presión específica media de laminación

b_3 Velocidad de deformación

b_4 Relación de potencia

b_5 Temperatura de trabajo

b_6 Aumento de temperatura por deformación

2.3. Equipos y material usados

Se utilizaron dos laminadoras, una de alta precisión para reducciones medias (Fig. 1), y otra de desbaste para grandes reducciones. Se medía presiones con celdas de carga hechas con "strain gages" y se registraban, como muestra la Fig. 1, además los equipos accesorios necesarios: microscopios, máquinas de ensayos, etc. El material utilizado fué aluminio de pureza comercial tipo 1100, analizado espectrográficamente en cada caso y con distintos grados de endurecimiento.

2.4. Método de trabajo

Se efectuaba la preparación superficial de las probetas. Se colaminaba con distintas reducciones y se cortaban probetas para ensayos mecánicos y metalografía. La Fig. 2 indica las entalladuras efectuadas para el ensayo tracción-corte y una probeta ya ensayada.

Cabe hacer notar la dificultad en la preparación de las probetas de tracción-corte, que recién dieron resultados satisfactorios a los seis meses de iniciado el trabajo.

3.   RESULTADOS OBTENIDOS Y DISCUSION

3.1.   Colaminación en frío

a)   Condiciones de superficie

Es bastante difícil, en un material como el aluminio, la separación de los distintos parámetros, pues ellos interactúan y forman parte de un to do que hemos llamado "preparación superficial".   Todas las probetas fue-ron desengrasadas en vapores de tricloroetileno, decapadas en baño alcali no y posteriormente en ácido y secada con lámparas infrarrojas.

a_i)   Oxidación: Se tomaron probetas pulidas y cepilladas, oxidán dolas a distintas temperaturas y tiempos colaminándolas pos teriormente.   Las probetas pulidas colaminaron entre 26 y 30%, las cepilladas entre 40 y 45%.

a_{ii})   Se cepillaron y se dejaron tiempos variables en aire, con dis tinta humedad ambiente.   Se observó que para tenores cre-cientes de humedad ambiente disminuía el tiempo en que se podría exponer la probeta luego de cepillada y antes de cola minar.

a_{iii})   Se cepillaron y se sellaron (evitando la posibilidad de conta-minación en el aire) dejándose tiempos variables antes de co laminar.   Se obtuvo una excelente unión incluso dos horas después del sellado.

a_c)   Endurecimiento por deformaciones previas: Se observa un aumento en la deformación mínima de colaminación y un apreciable aumento en la resistencia, en oposición a otros resultados.   La Fig. 3 muestra estos resultados.

a_5)   Rugosidad: Luego de distintas tentativas, se determinó que el aumento de rugosidad es perjudicial si las probetas son posteriormente oxidadas.
Con probetas cepilladas se observó metalográficamente en la interfase lagunas cuya microdureza es aproximadamente doble que la del material adyacente como se puede apreciar en la Fig. 4.

a_4)   Lo complejo de su estudio, hizo que en esta primera fase se descartara.

b)   Condiciones de laminación

b_1)   Se determinó para las distintas preparaciones superficiales

ya enunciadas, la deformación mínima necesaria de colaminación. Se trazaron las curvas de resistencia de unión en función de la deformación. Fig. 3.

b$_2$)   Para algunas condiciones se midió la fuerza separadora y se determinó la presión específica media de laminación. Se trazaron curvas en función de la deformación. Fig. 5.

b$_3$)   Calculada la máxima variación de la velocidad de deformación se obtuvo entre 350%/seg a 450%/seg, lo que hace que se pueda suponer constante este parámetro.

b$_4$)   La relación de potencia, altura inicial del material dividida por el diámetro del rodillo, se mantuvo constante en 4.75% en las dos laminadoras.

b$_5$)   La temperatura de trabajo era la ambiente.

b$_6$)   Según fórmula empírica de Siebel, se apreció que no era muy grande el aumento de temperatura por trabajado. Este parámetro se tuvo en cuenta para asegurar que no entrábamos a temperaturas de recuperación.

.2.   Colaminación en caliente

a)   Condiciones de superficie

Desaparece el efecto del endurecimiento previo y de la energía almacenada. Se trabajó entre 550º y 600ºC. Las probetas fueron desengrasadas y decapadas y secadas.

Se determinó que, para los tiempos de calentamiento necesarios (del orden de 30 minutos) la rugosidad resultaba perjudicial, obteniéndose uniones más limpias y con menor deformación mínima de colaminación, para probetas pulidas químicamente. La oxidación se estudió dejando tiempos crecientes en el horno. La deformación mínima de colaminación era de 7% para 30 min. a 600ºC, y subía a 20% para 180 minutos a 600ºC.

b)   Condiciones de laminación

En general puede decirse que continúan teniendo validez las de colaminación en frío.

4. CONCLUSIONES

4.1. Condiciones para obtener unión por colaminación

Del análisis de las condiciones de laminación surge claramente que, todos aquéllos parámetros que de alguna manera aumentan la fuerza separadora y, por lo tanto, la presión específica media de laminación, incrementará la resistencia de la unión. Tal es el caso del endurecimiento por trabajado previo. Dicho en otras palabras, para incrementar la resistencia de la unión interesa la presión aplicada. Esto es válido para colaminación en frío y en caliente.

Las condiciones de superficie afectarían el umbral mínimo de unión. Al estudiar esas condiciones, ciertos parámetros tienden a disimular el efecto de otros, pero puede decirse en forma general que es fundamental eliminar la zona contaminada para obtener unión. En ambos casos de colaminación en caliente y en frío, es preferible la formación de óxidos frágiles, aunque sean de mayor espesor, que la de óxidos que sigan la deformación.

Pareciera claro que la unión se efectúa en la diferencia entre la zona deformada y la superficie inicial, que si el óxido es frágil se mantendría constante. Las figuras 6 y 7 muestran ésto para deformaciones cercanas al umbral mínimo con diferentes aumentos.

El efecto de la rugosidad no pareciera claro, en la colaminación en frío. En caliente es evidentemente perjudicial por la gran oxidación que desarrolla.

4.2. Dispersión de resultados

La bibliografía presenta una gran dispersión de resultados. No sería incorrecto suponer que ello se debe a dos factores:

a) la dificultad para obtener ensayos mecánicos sencillos y reproducibles que midan la resistencia de unión de las probetas colaminadas

b) la dificultad en asegurarse la eliminación total de la zona contaminada. Esto se obviaría efectuando la colaminación en alto vacío, pero no se tienen datos a la fecha.

4.3. Temas en ejecución y a efectuarse

Se ha iniciado una sistemática tendiente a aclarar mejor el efecto de la rugosidad en la colaminación en frío.

Igualmente se trabaja en observar la distribución de óxidos para altas de-

formaciones procurando relacionar la superficie de unión con la resistencia de unión:

a) Se considera interesante estudiar el efecto de la energía superficial almacenada sobre la unión.

b) Estudiar en grandes cristales la facilidad de unión en función de las orientaciones relativas de las dos caras a unir.

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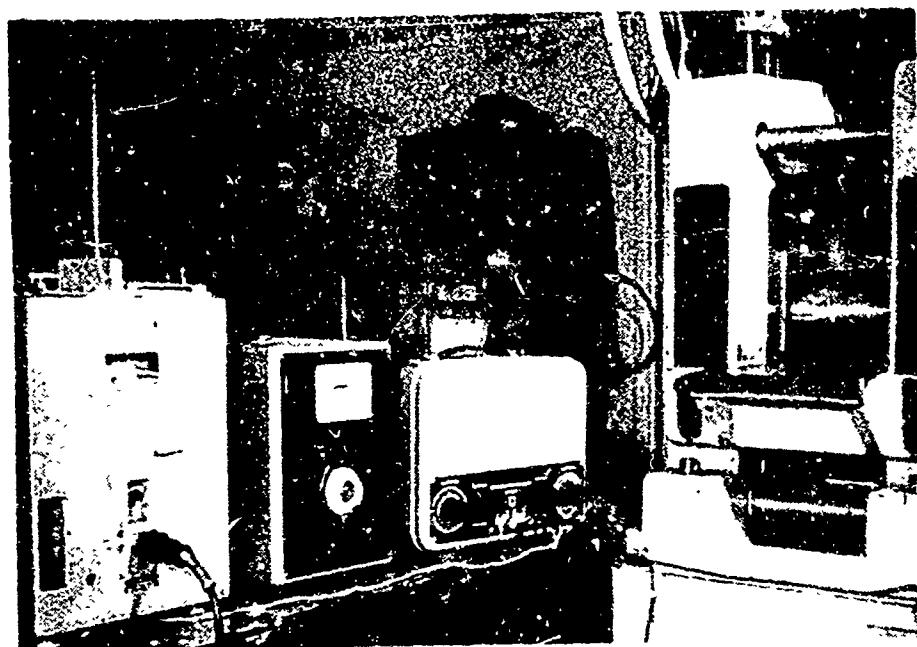
Figura 1   Laminadora, Equipo de Medición de Presiones y
              Sistema de Registro
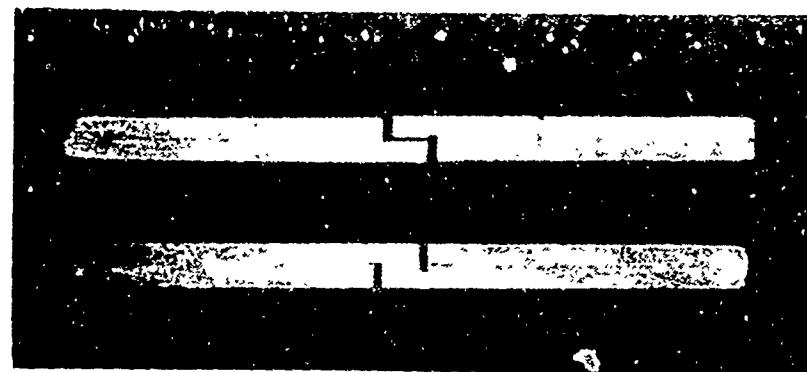
Figura 2   Probeta Entallada, Dispuesta para el Ensayo y Probeta
              luego de éste Mostrando la Rotura sobre la Interfase
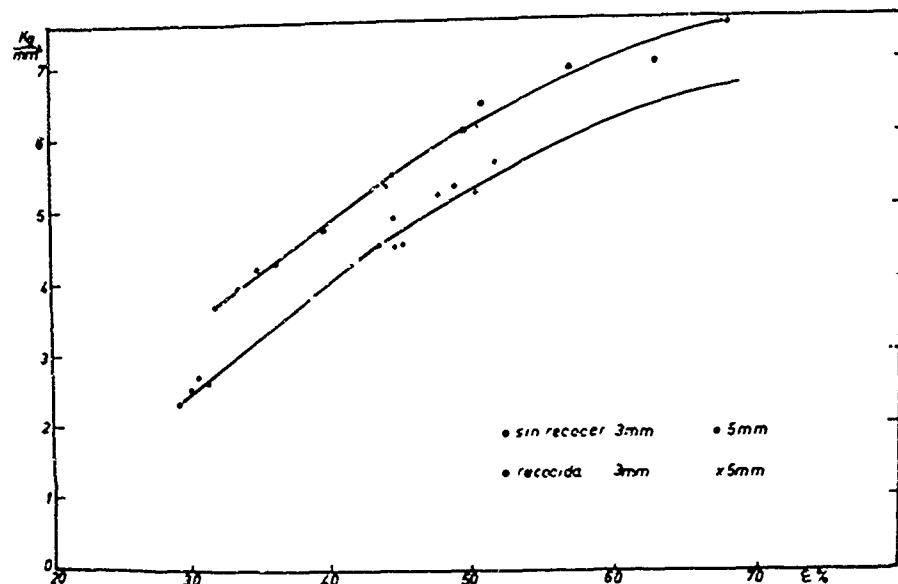
Figura 3   Resistencia de la Unión Colaminada

Figura 4   Impresiones de Microdureza en la Interfase de Al-Al
                Colaminado en Frío   325 X
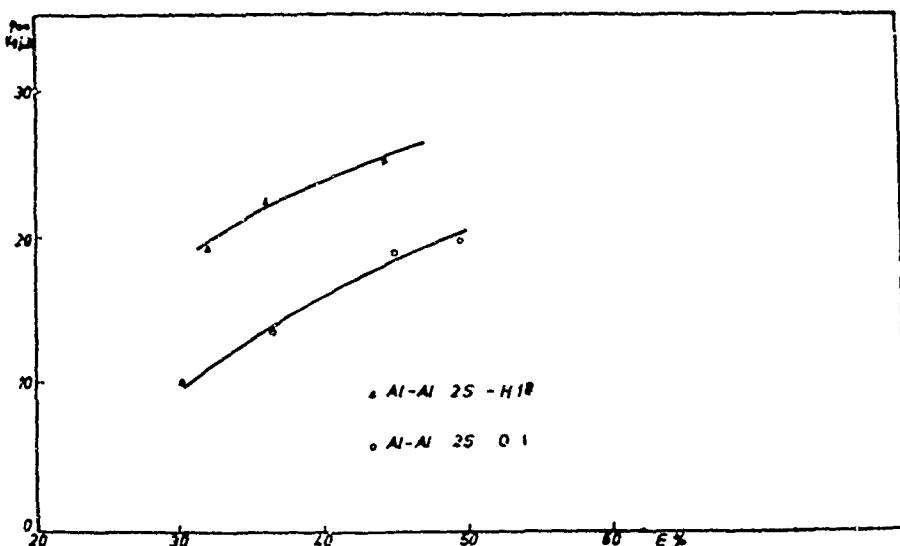
Figura 5   Presión Específica Media
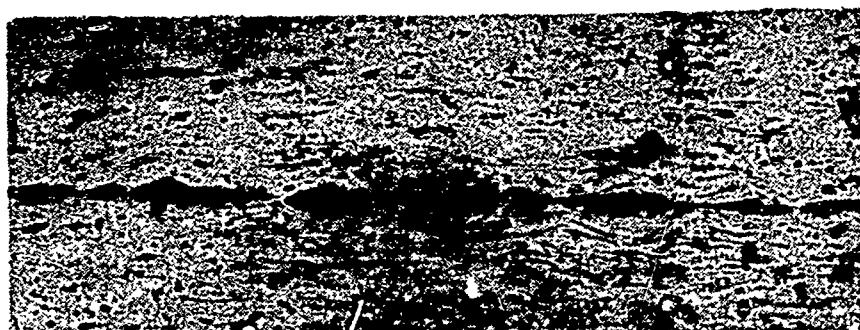
Figura 6   Micrografía de la Interfase de Unión para 30 seg. de
Exposición al Aire. Ataque: Agua Regia Fluorada   80 X
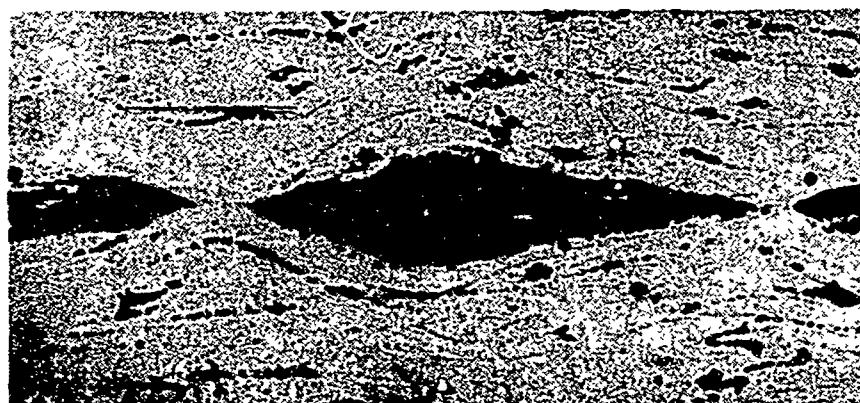
Figura 7   Micrografía de la Interfase de Unión presentando Lagunas
Cerradas de Oxidos. · Ataque: Reactivo de Milner   400 X

INFLUENCIA DEL EFECTO DE TAMAÑO Y ENTALLADURA EN LA RESISTENCIA A LA FATIGA DE ELEMENTOS ESTRUCTURALES Y DE MAQUINAS

por

Ing. Roberto Kuguel

Introducción

Desde un punto de vista práctico, la resistencia a la fatiga, tal cual se determina en experiencias de laboratorio, es útil en la medida que sus resultados pueden ser trasladados de la pequeña probeta utilizada generalmente en el laboratorio, a ' tamaño real de la parte estructural en cuestión.

Para trasladar los valores de la resistencia a la fatiga de las pequeñas probetas de laboratorio a la pieza real, debe considerarse por lo menos la influencia de cuatro variables: la entalla, la variación de resistencia a la fatiga con el volumen (efecto de tamaño), la forma del elemento real, y la posible diferencia en la forma de aplicación de la carga.

En este estudio, se considerarán qué iguales condiciones tienen lugar en las probetas y elementos estructurales, con respecto a las otras variables.

Cada uno de los factores arriba mencionados han recibido la cuidadosa atención de muchos investigadores, que han tratado el problema desde algún punto de vista particular: la influencia de la entalla, la disminución de la resistencia a la fatiga con el diámetro, el comportamiento de diferentes conformaciones bajo cargas repetidas, etc. Desgraciadamente los resultados no fueron siempre concordantes, no habiendo sido posible compararlos debido a la ausencia de un factor común apropiado.

Propósitos y Alcance

El presente estudio trata de los diversos factores geométricos que intervienen en el problema del diseño bajo cargas repetidas en metales. esto es la entalla, los efectos de tamaño y forma, y la influencia de los diferentes tipos de cargas. Es su objeto encontrar una expresión simple suficientemente generalizable y

razonablemente segura, a fin de su inmediata aplicación al diseño.

Como parámetro o factor común, se investiga la influencia del volumen altamente tensionado de material.

Aunque se delinea un procedimiento general, el alcance de este estudio concierne primariamente a estado de flexión, debido a la falta de datos apropiados para otros tipos de carga.

Análisis

Es el propósito de este análisis, encontrar una expresión aplicable al problema de diseño bajo cargas repetidas. Trata de algunos de los factores que gobiernan la fractura por fatiga en probetas metálicas sometidas a momentos flexores o torsores.

Gradiente de Tensión

La superficie, que es donde se inician con mayor frecuencia las fisuras, tienen una gran influencia en la rotura por fatiga; luego, su estado merece una cuidadosa atención en todo estudio dirigido al diseño.

Para un metal dado, puede definirse la superficie con el conocimiento de las siguientes variables: 1) ambiente, 2) rugosidad, 3) tensiones residuales, y 4) gradiente de tensiones. Se supondrán constantes los tres primeros y consideremos pues el gradiente de tensiones, definido como:

$$G = \frac{d \; \sigma \, max}{dy} \; \frac{1}{\sigma \, max} \; \left(\frac{1}{cm}\right) \qquad (1)$$

Para probetas lisas, sometidas a flexión, el valor de G es inmediato:

$$G = 2/d \qquad (2)$$

Para otros tipos de probetas, es posible derivar expresiones apropiadas, partiendo de las fórmulas de Neuber (ref. 1). Para probetas con entallas profundas sometidas a flexión o torsión, las derivaciones fueron dadas por Uzhik (ref. 2). En ref. 3 se dan ecuaciones aproximadas para computar G.

Punto de Vista Estadístico

La falla por fatiga es un fenómeno estadístico. Está la rotura asociada con defectos en el seno del material: la probabilidad de encontrar un defecto es proporcional al volumen del mismo. Luego, la probabilidad de falla aumenta con el volumen de material. Este argumento es la base que permitió el desarrollo de diversas teorías estadísticas de fatiga (refs. 4 y 5).

Volumen de Material Altamente Tensionado

Es posible combinar las premisas anteriormente expuestas, estableciendo consecuentemente que, dentro de un margen estadístico, dos probetas tendrán igual probabilidad de falla si ambas tienen el mismo volumen altamente tensionado. Por "volumen altamente tensionado" se entiende la delgada capa de material sometida a una tensión relativamente alta, por ejemplo 95% y más de σ max. Cualquier región o porcentaje podría haberse elegido, siempre que el gradiente de tensión en la misma fuera aproximadamente lineal.

De ser cierta esa aseveración, la resistencia a la fatiga no dependería ya, entre otros factores, del diámetro de la probeta sino del volumen mencionado. Además, debe recalcarse que un mismo valor de ese volumen puede alcanzarse en una probeta pequeña lisa, y en otra entallada, con mayores, apropiadas dimensiones.

Efecto del Tamaño

La hipótesis será aplicada en primer término al efecto de tamaño, esto es la disminución de resistencia a la fatiga observada en piezas metálicas, cuando su tamaño aumenta. En primer término se trató de correlacionar el efecto de tamaño con la resistencia a la fatiga σ_f y la resistencia estática σ_u. Aunque sería dable esperar que los resultados en un diagrama σ_f vs σ_u se separaran en bandas que contendrían diferentes rangos de diámetro, ello no tuvo lugar.

Un segundo intento de correlación se efectuó entonces, ploteando el logaritmo del volumen altamente tensionado arriba mencionado versus logaritmo σ_{max}. Para ello se utilizaron resultados provenientes de trabajos de D. Morkovin y H. F. Moore (ref. 6), y H. F. Moore y T. J. Dolan (ref. 7).

El volumen altamente tensionado fue determinado tomando en cuenta el gradiente de tensión y las siguientes hipótesis simplificativas (ver fig. 1 y ref. 8):

1.   El área A será considerada triangular.
2.   La distancia d' entre centros de gravedad de las áreas A es aproximadamente igual al diámetro d de la probeta.
3.   El volumen V está sometido a un momento flexor puro.
4.   El factor K_t no modifica su magnitud desde d a d_1.

Las hipótesis 3 y 4 dependen para su justificación de la distancia ΔL, a cual en la gran mayoría de los casos es lo suficientemente pequeña para ello.   Los resultados muestran (fig. 2) una relación pronunciadamente lineal (*).   La línea recta resultante puede ser representada por la ecuación:

$$\sigma_{max} = B \cdot V^{-a} \tag{3}$$

A fin de hacer este procedimiento aplicable a problemas prácticos, esa recta fue dibujada a través de un valor experimental que tiene, en cada caso, el mismo volumen altamente tensionado: $V_1 = 0.000349$ pulg^3. Este volumen corresponde a una probeta lisa de d = 0.25 pulg, y r = 1.25 pulg. Luego, los parámetros de la ecuación (3) tendrán los siguientes valores:

$$B = 0.136 \; \sigma_{max\,1}$$

donde $\sigma_{max\,1}$ es la tensión máxima para V_1, y

$$a = 0.034$$

En la fig. 2 están representadas estas rectas y las correspondientes a una banda de dispersión de $\pm 10\%$. Como puede observarse, todos los puntos yacen dentro de esas bandas, excepto dos.

Efecto de la Forma y del Tipo de Carga

El procedimiento anterior destinado a determinar el volumen de material altamente tensionado, no se ve restringido a la utilización de probetas con igual forma transversal o tipo de carga. Por ello, la técnica utilizada fue extendida a diversos casos seleccionados de las referencias 9 y 10.

La fig. 3 muestra el comportamiento de probetas de aleación de aluminio 24S-T en ensayos de flexión alternativa y rotativa, ref. 9. Como en este caso no hay probetas con el "volumen índice" $V_1 = 0.000349$ pulg^3, no es posible aplicar la ecuación (3). Sin embargo, se observa que las probetas siguen la tendencia general. También de la misma figura es posible observar que probetas con secciones transversales con esquinas agudas, tienen una definida reducción de resistencia, además del efecto de forma ya mencionado. En la figura anterior - número 2- se ha incluido también resultados para un acero SAE 4340, correspondientes a 4 diferentes formas de sección transversal, bajo flexión alternada. Estos resultados yacen dentro de la misma banda de dispersión determinada para el mismo acero, en ref. 7. No se han efectuado correcciones tendientes a considerar la pequeña diferencia de propiedades estáticas entre ambos aceros SAE 4340.

(*) Como la mayoría de las probetas utilizadas en los estudios aquí detallados fueron construidas con la libra y pulgada como unidades de medida, se ha preferido seguir este sistema para desarrollar los resultados obtenidos.

Ensayo   Estático

Finalmente y escapando un poco del alcance establecido para este estudio, se da en la fig. 4 resultados de tensión de fluencia medida en ensayo estático: se da allí valores de la tensión de fluencia en función de log. V, según resultados dados en ref. 11. Aquí también se observa una reducción lineal de la resistencia con V, aunque la inclinación resulta un poco mayor. No obstante, utilizando la misma pendiente que en los casos anteriores, la dispersión resulta ser menor del 20%.

Relación Entre K_t y K_f

Es bien sabido que la mayoría de los metales no muestran una reducción de su resistencia a la fatiga tan importante como la predicta por el"factor teórico de concentración de tensiones" K_t, definido como

$$K_t = \frac{\sigma \max}{\sigma \text{ nom}} \qquad (4)$$

Es por ello que el factor empírico K_f, dado por la expresión siguiente:

$$K_f = \frac{\sigma \text{ fs}}{\sigma \text{ fn}} \qquad (5)$$

debe ser usado en el diseño. La desigualdad $K_f < K_t$ ha sido observada repetida-mente en la práctica. La explicación más extendida al respecto se basa en consideraciones acerca de la deformación inelástica en la raíz de la entalla. Sin embargo, ella no da una explicación completa y consistente acerca del fenómeno. La cuestión importante que sobreviene, es la predicción del valor apropiado de K_f. Para solucionar este problema, Peterson (ref. 12) introdujo el importante concepto de "factor de sensibilidad a la entalla" q, definido como:

$$q = \frac{K_1 - 1}{K_t - 1}$$

Este factor tiene el mérito de suministrar una escala para la medición de la sensibilidad a la entalla, que varía entre q = 0 (efecto de entalla nulo) y q = 1 (efecto de entalla total). Peterson sugiere que q depende del radio r_n en el fondo de la entalla y de la dureza del material. Sin embargo, se considera que r_n no constituye una completa representación de la entalla. Además, se ha observado que q es muy sensible a los valores experimentales y a la dispersión de los resultados. Aquí se considerará la relación entre los coeficientes K_t y K_f, a la luz del

concepto de volumen altamente tensionado.

Analisis

Introduzcamos en la ecuación (5), la fórmula empírica descripta en (3):

$$K_f = \frac{\sigma\, fs}{\sigma\, fn} = \frac{B \cdot V_s^{-a}}{\underbrace{B \cdot V_n^{-a}}_{K_t}} = K \left(\frac{V_s}{V_n}\right)^{-a}$$

finalmente

$$\frac{K_f}{K_t} = \left(\frac{V_n}{V_s}\right)^{0.034} \tag{6}$$

Considerando ambas probetas, la lisa y la entallada, de igual diámetro, es evidente que V_n será menor que V_s; consecuentemente, K_f será siempre menor que K_t. Se dará a continuación la relación entre K_f y K_t para probetas con entallas poco profundas, sometidas a flexión rotativa y carga axial repetida.

Para una probeta de diámetro d y radio del pedil r, la expresión para V, según se ha podido comprobar, está dada por:

$$V \cong 0.02 \, \frac{\sqrt{r \cdot d}\; d}{G} \tag{7}$$

Para probetas lisas, según (2) resultará:

$$V_s = 0.01 \sqrt{r_s \cdot d_s^5} \tag{8}$$

Y para probetas con entallas poco profundas $G = 2.5/r_n$. Luego en (7):

$$V_n \cong 0.008 \sqrt{r_n^3 \cdot d_s^3} \tag{9}$$

Teniendo en cuenta estas dos últimas expresiones, la ecuación (5) puede ser escrita así:

$$\frac{K_f}{K_t} = \left[0.8 \sqrt{\frac{r_n^3 \cdot d_n^3}{r_s \cdot d_s^5}} \right]^{0.034}$$

y para $d_n = d_s = d$:

$$\frac{K_f}{K_t} = (0.8)^{0.034} \cdot \frac{r_n^{0.051}}{r_s^{0.017} \, d^{0.034}} \tag{10}$$

Luego, la relación entre K_f y K_t depende solamente de la geometría de la sección crítica de ambas probetas, lisa y entallada, y no del material. En la par te B de la Discusión se volverá sobre este punto.

La incidencia de cada una de las características geométricas r_n, d y r_s puede pesarse de acuerdo a la siguiente expresión:

$$\frac{d\,(K_f/K_t)}{(K_f/K_t)} = \pm \frac{\frac{\partial\,(K_f\,K_t)}{\partial\,r_n}d_{r_n}}{K_f\,K_t} \pm \frac{\frac{\partial\,(K_f\,K_t)}{\partial\,r_s}d_{r_s}}{K_f\,K_t} \pm \frac{\frac{\partial\,(K_f/K_t)}{\partial\,d}d_d}{K_f/K_t}$$

Reemplazando las derivadas por sus valores y simplificando, resulta:

$$\frac{d\,(K_f/K_t)}{(K_f/K_t)} = \pm 0.051 \frac{d\,r_n}{r_n} \pm 0.017 \frac{d\,r_s}{r_s} \pm 0.034 \frac{d\,d}{d}$$

Luego, la variación de r_n tiene un efecto tres veces mayor que el de r_s, y 1.5 el de d.

De la consideración de una amplia gama de forma de probetas, se ha podido concluir que es fundamentalmente r_n el factor que puede modificar sustancialmente la relación entre K_f/yK_t: una gran variación en las características geométricas de probetas lisas, sólo provocó un 15% de variación en la antedicha relación. Es por ello que, sin temor a errores importantes, puede tomarse las dimensiones de una probeta generalizada, lisa, de fatiga, como base para el análisis.

La fig. 5 resulta de considerar una probeta de d - 0.3 pulg., y r_s 10d. En estas condiciones, la (10) se transforma en:

$$K_f = K_t . 1.0148 (r_n)^{0.051} \tag{11}$$

En la misma figura se han incluído 112 resultados experimentales tomados de ref. 13. Los valores de K_t variaron entre 1.4 y 2.8. Se observa que aproximadamente el 78% de los resultados yacen dentro de la banda de dispersión $\pm 10\%$.

A continuación se analizará la relación entre K_t y K_t para placas bajo car ga axial repetida. En este caso, se ha podido determinar que los volúmenes V_s y V_n están dados por

$$V_s = 0.46 \sqrt{r_s} . b_s \quad t . b_s$$

para probetas lisas. En el caso de probetas con entallas poco profundas:

$$V_n = 0.018 \sqrt{r_n} . b_n \quad t . r_n$$

y para entallas profundas

$$V_n = 0.024 \sqrt{r_n \cdot b_n} \quad t. r_n$$

Estas ecuaciones fueron utilizadas para determinar los valores de K_f en placas sometidas a cargas axiales. En la tabla siguiente los valores computados se comparan con resultados experimentales extraídos de ref. 14 y 15.

K_t	K_f calculado	K_f experimental		
		Para aleación 24S-T3	Para aleación 75S-T6	Para acero SAE4130
2	1.8	1.8	1.9	1.9
2	1.6	1.8	1.9	1.7
2	1.6	1.8	1.9	1.7
4	3.0	3.1	4.0	3.4
4	2.8	2.4	3.2	2.8
5	3.6	3.4	5.0	4.7

Una banda de dispersión de $\pm 10\%$, incluiría el 58% de los 18 resultados compulsados.

Discusión

A.   Bases para la selección de la banda de dispersión de $\pm 10\%$

Dos características de los resultados de experiencias sobre fatiga que afectan la exactitud de la medición de la sensibilidad a la entalla, son la gran dispersión de los resultados y la influencia potencialmente importante de diversas variables "accidentales".

Se verán a continuación algunos de los factores que producen errores sistemáticos:

1.   Forma de preparación de la probeta.
La resistencia a la fatiga de probetas realizadas con el mismo material pero en diferentes talleres, y aun en el mismo taller pero con diferentes

operarios, puede diferir grandemente. Ese comportamiento irregular está provocado por las variaciones en las tensiones residuales, trabajado mecánico y rugosidad superficial introducidas por las diferentes técnicas empleadas en el mecanizado y pulido de probetas.

Gohn y Fox (ref. 16), han registrado por ejemplo, una diferencia del 25% en la resistencia a la fatiga de probetas de bronce fosforoso en ensayos de flexión rotativa, que habían sido maquinadas por dos diferentes talleres, pero ambos siguiendo los procedimientos normalizados por A. S. T. M. en el manual de ensayos de fatiga (ref. 17).

Aun en el caso de que las probetas sean preparadas por el mismo operario, las diferencias en los radios de las probetas lisas y las entalladas hace generalmente imposible utilizar la misma técnica de maquinado y pulido. Estos factores pueden introducir una diferencia sistemática y una falta inherente de reproducibilidad entre determinaciones experimentales de la sensibilidad a la entalla que, desde otro punto de vista, podrían ser totalmente comparables.

2   Influencia de las condiciones ambientales generalmente no controladas durante la experiencia.

La mayoría de los ensayos de fatiga efectuados a temperatura ambiente, se realizan sin control seguro de las condiciones ambientales variables periódicamente, tales como la temperatura y el contenido de humedad del aire del laboratorio. No obstante, estas variables pueden tener una pequeña pero concreta influencia en la vida de las probetas.

Así Liu y Corten (ref. 18) establecieron que el contenido de agua del aire influye en la vida a la fatiga de probetas de aleaciones de aluminio sometidas a tensiones repetidas: un incremento del contenido de agua desde 12 granos a 120 granos, por libra de aire seco, disminuyó la vida de fatiga por un factor aproximadamente igual a dos.

3.   Naturaleza estadística del fenómeno de fatiga.

La fuente más importante en la dispersión azarosa de los valores experimentales de K_f reside en la naturaleza estadística misma del fenómeno de fatiga. Las heterogeneidades en el seno del material son los orígenes de las fisuras por fatiga y de la fractura consecuente. Probetas individuales de una dada población estadística exhiben una gran dispersión tanto en la vida como en la resistencia a la fatiga. En las determinaciones experimentales de K_f resumidas en la fig. 5, fue una práctica normal basar el valor de K_f en los resultados de diversas probetas ensayadas en la región del límite de fatiga (o resistencia a la fatiga a 10^7 ciclos). Cada investigador utilizó un gran número de probetas, pero el valor de K_f fue determinado por las pocas probetas ensayadas a tensiones muy cercanas a la resistencia a la fatiga. Luego, es válido preguntarse la importancia de la dispersión que puede estar presente en los resultados arriba mencionados. La respuesta puede provenir de la examinación de la variabilidad estadística, esto es la desviación standard que debe ser asociada a la resistencia a la fatiga.

Ensayos cuidadosamente planeados y controlados, donde todo aquello que no sea dispersión por fuente estadística fue minimizado, dieron los siguientes resultados (ref.19):

Material	$\sigma'_{f(ksi)}$	$\pm 0.10\sigma'_f$	+1 desviación standard	+ 2 desviaciones standard
SAE 1050	40.8	4.1	1.0	2.0
Hierro Armco recocido	29.3	3.0	2.3	4.6
SAE 4340 templ. y esferoidiz.	62.5	6.3	2.7	5.4
SAE 43440 templ. y normaliz.	97.6	9.8	7.2	14.4

La tabla anterior indica que una banda de dispersión de $\pm 10\%$ cubre un rango levemente mayor a una desviación standard en dos casos, levemente superior a dos desviaciones standard en un tercer caso y cerca de 4 desviaciones standard en el cuarto.

Siendo K_f la relación de dos valores de resistencia a la fatiga, es apropiado determinar cómo la desviación standard de K_f está relacionada con ellos. Para un cociente tal como

$$K_f = \frac{\sigma_{fs}}{\sigma_{fn}}$$

la desviación standard está dada por (ref. 20)

$$S^2_{K_f} = \bar{K}_f^{-2} \frac{S^2_{\sigma_{fs}}}{\sigma^2_{fs}} + \bar{K}_f^2 \frac{S^2_{\sigma_{fn}}}{\sigma^2_{fn}} \tag{12}$$

donde $\bar{K}_f$, $\tilde{\sigma}_{fs}$ y $\tilde{\sigma}_{fn}$ son los valores medios de K_f, σ_{fs} y σ_{fn} respectivamente.

De la (12) puede deducirse la siguiente expresión, donde

$$S\sigma'_{fs} = \alpha . S\sigma'_{fn}$$

y en donde frecuentemente $\alpha \gg 1$, desde el momento que las probetas entalladas exhiben menos dispersión que las lisas:

$$\frac{S_{K_f}}{\bar{K}_f} = \sqrt{\left(\frac{\alpha}{(\bar{K}_f)^2}\right)^2 + 1} \frac{S_{\sigma_{fn}}}{\bar{\sigma}_{fn}} \tag{13}$$

Es obvio que la relación

$$S_{K_f} / \bar{K}_f$$

es mayor que el cociente

$$S_{\sigma'_{fs}/\ddot{\sigma}_{fn}}$$

y (como se puede mostrar en forma análoga) de

$$S_{\sigma_{fn}/\ddot{\sigma}_{fn}}$$

pues el valor del término bajo la raíz es necesariamente mayor que la unidad. Luego, el ancho de la banda de dispersión de K_f expresada en porcentaje de K_f, es mayor que la banda de dispersión asociada con $\tilde{\sigma}_{fs}$ o $\tilde{\sigma}_{fn}$.
Una vez acumuladas las fuentes de dispersión arriba mencionadas, puede concluirse que la banda de dispersión de $\pm 10\%$, da una estimación conservativa de la dispersión que debe esperarse en determinaciones de $K_f/$, siempre que una ocurrencia de características especiales del material, geometría de la probeta, etc., no concurran para dar una falta bastante inusual de dispersión.
De los resultados que se muestran en la fig. 5, donde el 78% de los 112 puntos incluídos caen dentro de esa zona de dispersión, puede estimarse que la banda de $\pm 10\%$ corresponde aproximadamente a 1.2 desviaciones standard.
Si bien un análisis más exacto de la dispersión sería deseable, la falta de resultados tratados estadísticamente, lo hace en la actualidad imposible.

B.   Alcance y limitaciones de la presente tentativa

El autor de este estudio supone que otras características geométricas, además del ya mencionado volumen V, tienen una influencia, aunque pequeña, en la relación entre K_f y K_t. Entre ellas podrían encontrarse los siguientes factores: dureza del material, heterogeneidades de la estructura cristalina y deformaciones plásticas localizadas.

Para el objeto de una estimación apropiada de K_f a usar en el diseño, se sugiere pues modificar K_t según el concepto del "volumen altamente tensionado" tal como fue expresado en la ecuación (6). Según los resultados dados en la fig. 5 puede anticiparse que en 4 de cada 5 casos, el valor de K_f así determinado, estará dentro de $\pm 10\%$ de error.

Conclusiones

Los resultados de este estudio parecen justificar las siguientes conclusiones:

1.   La resistencia a la fatiga de los metales disminuye a medida que el volu-
men tensionado de material en la superficie, aumenta. Una región alta-
mente tensionada que cubra, por ejemplo 95% y más de σ_{max}, puede ser
considerada para el diseño.

2.   Se ha encontrado una función lineal, con una pendiente suficientemente inva-
riable para muchos metales, en la relación entre el logaritmo del volumen
V y la tensión máxima del material. La ecuación de esta recta puede defi-
nirse para un dado material conociendo solamente un valor de resistencia a
la fatiga: la tensión máxima para $V_1 = 0.000349$ pulg^3, que corresponde a
una probeta lisa de 0.25 pulg de diámetro y r = 1.25 pulg, sometida a un en-
sayo de flexión rotativa.
Comparando esta ecuación con resultados existentes en ensayos de flexión
alternada y rotativa, se encontró un error máximo de 10%.

3.   Partiendo del mismo concepto, es posible inferir la desigualdad $K_f < K_t$.

4. K_f depende de K_t, el radio de las probetas lisas y entalladas y del diáme-
tro d; sin embargo, la influencia de K_t y el radio de la probeta entallada,
son los factores más importantes.

5.   La relación entre K_f y K_t para probetas sometidas a flexión rotativa, está
registrada en la ecuación (10) y en la fig. 5. Examinados resultados expe-
rimentales, se observó que el 78% de los resultados estuvieron incluidos
dentro de una banda de dispersión de $\pm 10\%$.

6.   Experiencias ulteriores, actualmente en desarrollo, permitirán verificar
sistemáticamente las expresiones aquí adelantadas.

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NOTACION

A	Area formada por la intersección del volumen altamente tensionado V, con un plano pasante por el eje de la probeta.
a	Exponente.
B	Coeficiente dependiente del material.
b	Ancho de una placa.
d	Diámetro crítico o más pequeño, de una probeta.
d'	Diámetro de una probeta, en los extremos.
d_1	Distancia entre los centros de gravedad de las áreas A.
G	Gradiente específico de tensiones.
K_f	Factor real de entalla.
K_t	Factor teórico de concentración de tensiones.
q	Factor de sensibilidad a la entalla.
r	Radio del perfil de una probeta.
S	Desviación standard.
t	Espesor de una placa.
V	Volumen de una probeta, sometido a 95% y más de la tensión máxima.
Δ_1	Semibase del triángulo formado por el área A.
σ_F	Tensión de fluencia
σ_f	Límite de fatiga de un metal. (Para aleaciones de aluminio, la tensión correspondiente a 10^7 ciclos).
σ_{max}	Tensión máxima.
σ_{nom}	Tensión nominal.
σ_u	Tensión de rotura estática.

Subíndices

n	Para probeta entallada.
s	Para probeta lisa.
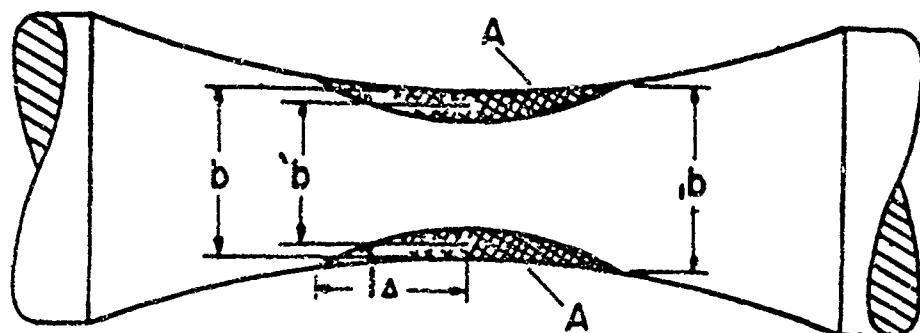
Figura 1   Características Geométricas y Distribución de Tensiones en el Area A de una Probeta para Flexión Rotativa
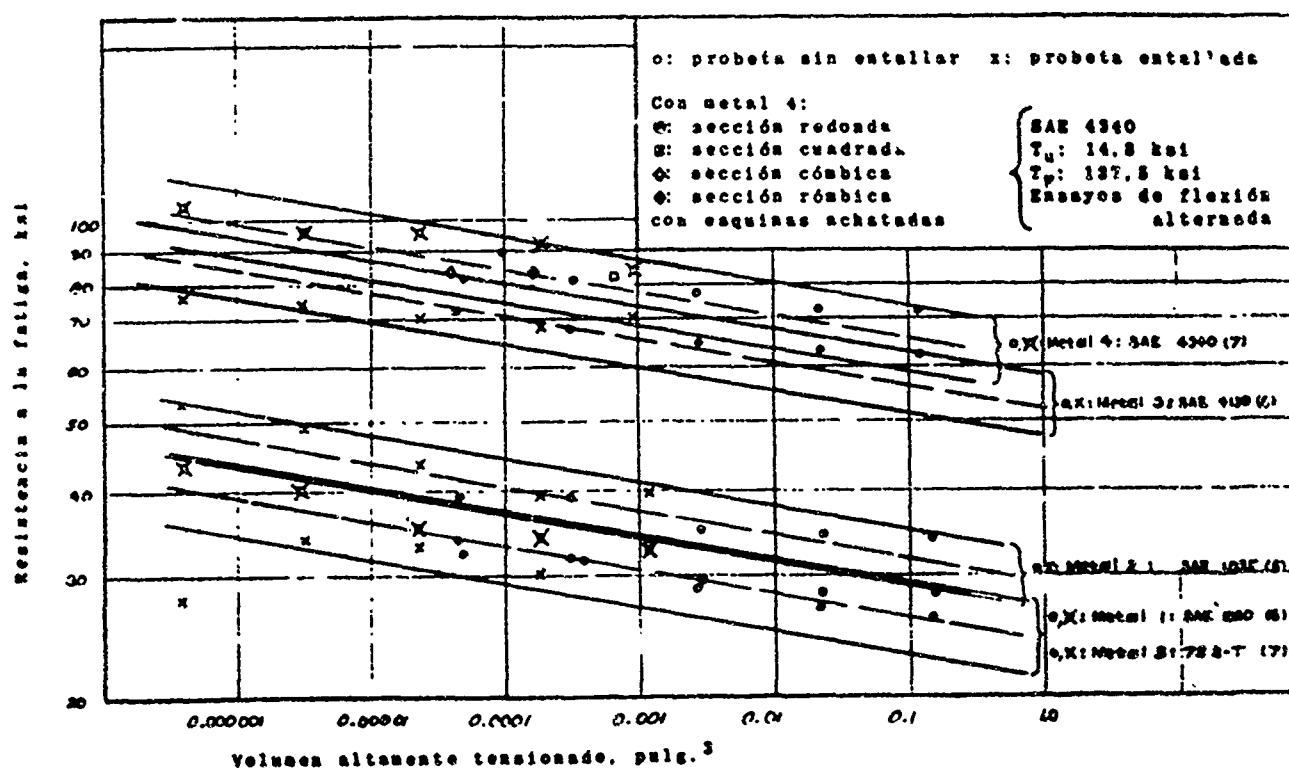
Figura 2   Relación entre la Tensión Máxima (K_t T_{nom}) y el Volumen Altamente Tensionado (Ref. 10)

●: Sección redonda, flexión altern
O: "   "   rotat.
◇: " rómbica, con esq.
agudas en flexión alternada.
◆: Sección rómbica modificada, en
flexión alternada.
▫: Sección cuadrada con esquinas
agudas en flexión alternada.
▪: Sección cuadrada modificada en
flexión alternada.

Volumen de material altamente tensionado, pulg^3

Figura 3   Relación entre la Tensión Máxima (K_t T_{nom}) y el
Volumen de Material Altamente Tensionado, para la
Aleación de Aluminio 24 SPT (Ref. 9)

Figura 4   Relación entre la Resistencia a la Fluencia y el
Volumen Altamente Tensionado. Ensayo Estático.
Material: Acero con 0,18% de C

Figura 5   Relación entre K_f y K_t para d = 0,3 pulg., r_s = 10 d, r_n = t = 0,003 a 0,090 pulg.

"ESTRATEGIA DE LA INVESTIGACION METALURGICA EN LATINO AMERICA"

por Jorge Sábato

Si el Dr. Villanueva comenzó su exposición diciendo que eran bases preliminares para una discusión de una metodología general, Uds. me van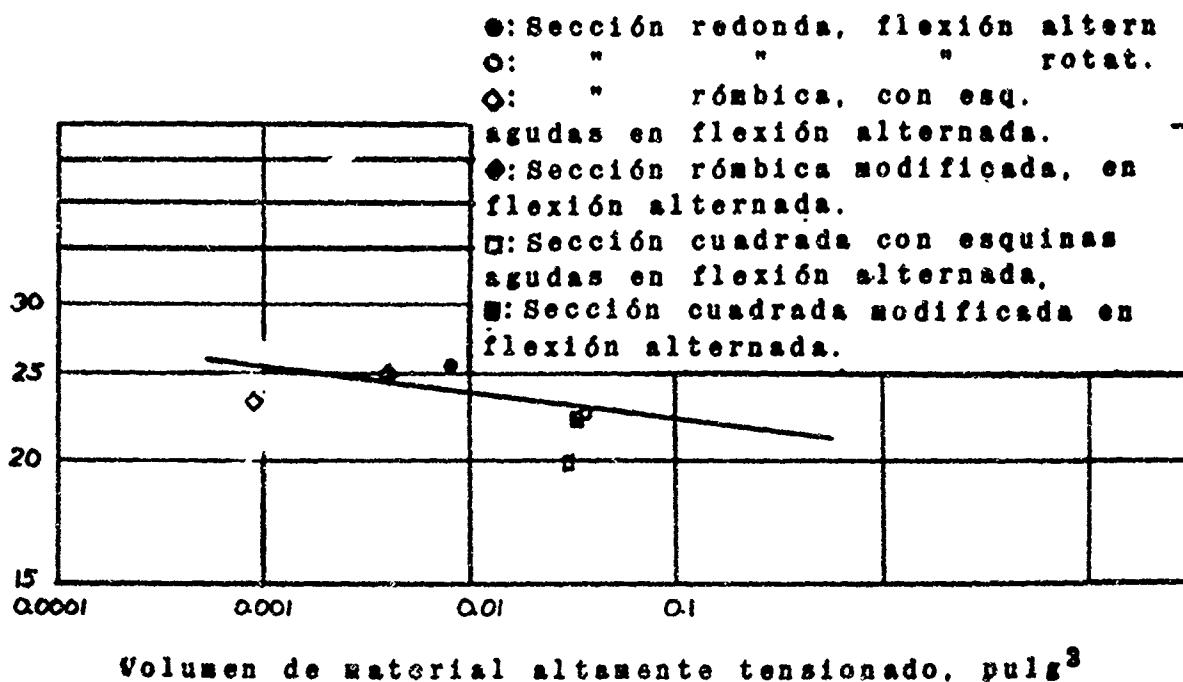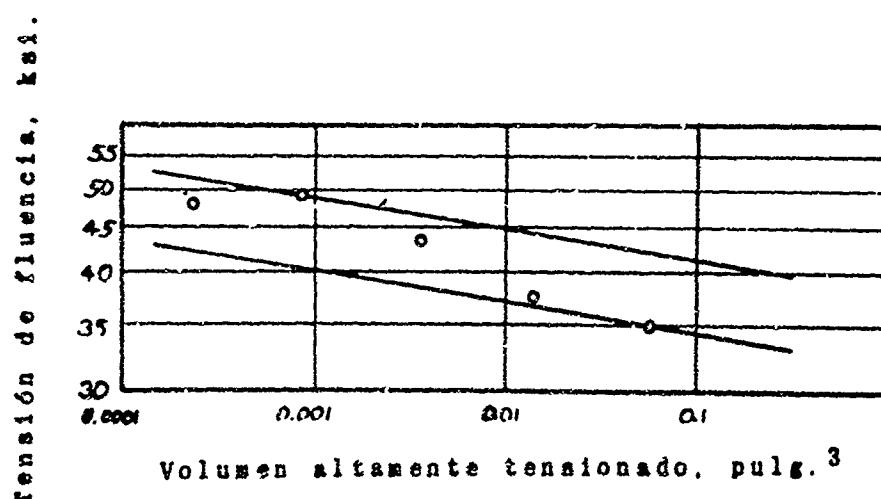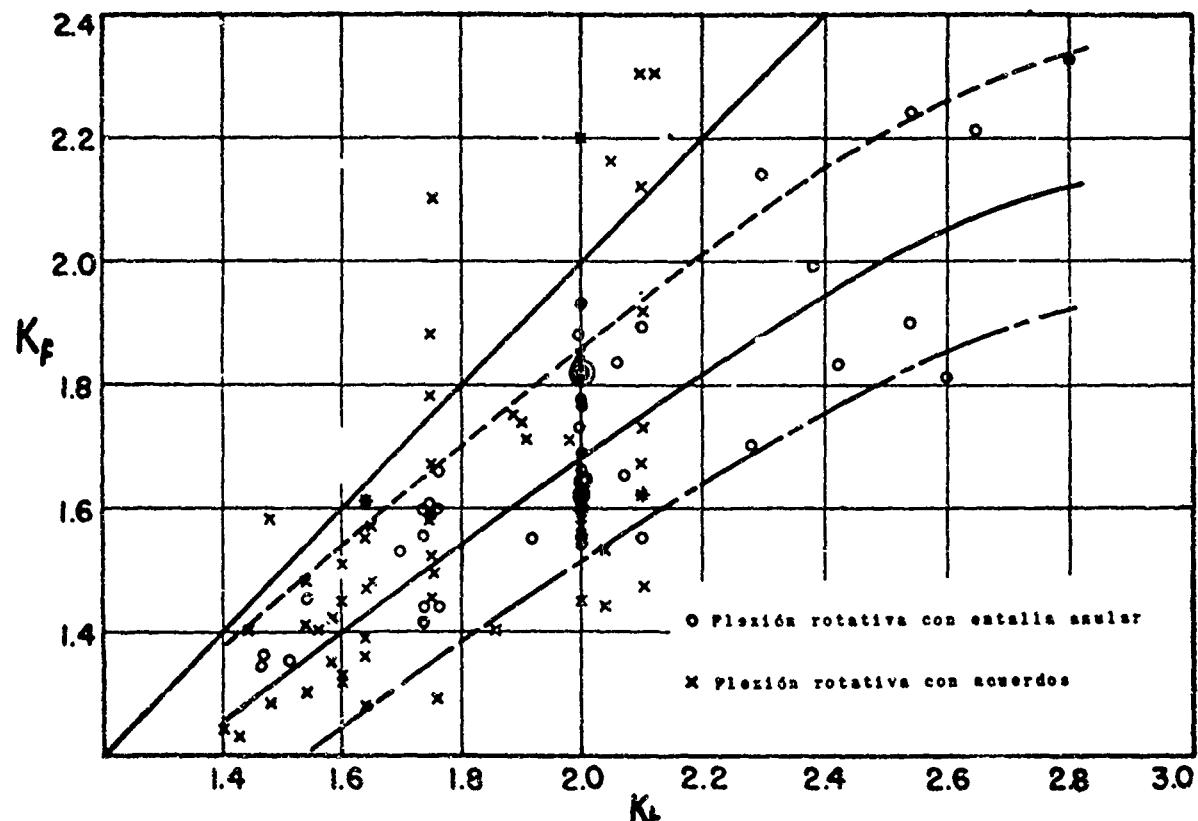 a disculpar, porque las mías son bases preliminares para las bases preliminares del Dr. Villanueva. De manera que traer este tema a esta reunión ha tenido un objetivo fundamental que es, como el de muchos otros que se han traído a esta conferencia, la de producir una determinada inquietud en los que trabajan en metalurgia, por un lado y en los que planifican la economía y el desarrollo por otro.

Corresponde naturalmente a una tendencia moderna que adquiere su aspecto más orgánico en los trabajos que realiza la O. E. C. D. en Europa. Por cuanto al tener que fijar y determinar la estrategia en varios países y al hacer cuenta de los recursos disponibles, la O. E. C. D. ha organizado comités especiales, meetings, reuniones de ministros de ciencia, etc., con el objeto de tratar de planificar o de fijar algunos términos de planificación para la investigación científica y/o técnica. El problema en términos generales es muy simple: frente al universo de cosas por investigar, evaluar los riesgos de la investigación, como lo expresara el Dr. Villanueva. En particular los riesgos medidos, no de una empresa particular, sino en una forma teórica general, para todo el mecanismo económico general. Teniendo en cuenta estos dos factores, no cabe ninguna duda que la preocupación. en particular en el caso de los miembros de la O. E. C. D., está fundamentada. Reflexionemos: si en el caso de la O. E. C. D., es decir en el caso de los países Europeos, esa preocupación está fundamentada, en países de estructura mucho más debil, como los países latinoamericanos, la fundamentación es muchísimo más obvia.

Si los recursos disponibles son escasos y si para emplear esos recursos disponibles no trazamos una estrategia adecuada, el rendimiento social de esos recursos será mucho menor todavía que si para los mismos dispusiéramos de una política inteligente. Por supuesto que estas son cosas generales por cuanto están en la base de la creación de los organismos denominados Consejos Nacionales de Investigación que existen en varios países latinoamericanos y que en los que no existen muy pronto se van a crear.

Pero es una preocupación moderna, por supuesto, es una preocupación que hubiera producido aberración no solamente a los economistas liberales sino a los

políticos liberales. Pero corresponden por otra parte a una realidad, que como siempre ocurre, es mucho más fuerte que los esquemas teóricos pre-existentes. En ciencia, como en otras actividades, habrá que planificar. Este es un imperativo. Conviene mucho que los que hacen investigación comiencen a pensar en este problema, por cuanto si nó, les ocurrirá lo que ha ocurrido en otras actividades: que serán planificadas de buenas a primeras, sin consultar su opinión y sin siquiera haber llegado a la preocupación del problema. Con el Dr. Villanueva revisamos bastante bibliografía sobre este tema, y encontramos que los tratamientos generales son débiles, que no hay una metodología a la cual podamos recurrir como criterio, como cartabón filosófico. Lo que hay son tentativas, aproximaciones al problema.

Toda vez que me encuentro que sólo hay aproximaciones tentativas en un problema, eso me alegra porque así tenemos chance de intervenir en la elaboración del mismo. Si el esquema teórico general -digo- es débil, la metodología misma está todavía en elaboración. Nosotros hemos pensado que lo interesante, por un lado sería tratar de hacer algún esquema teórico, como el que el Dr. Villanueva presentó, y por otro lado comenzar a aplicar algunas de esas ideas a una disciplina específica.

En lugar entonces de ocuparnos de la investigación científica, de la investigación tecnológica, como concepto general, entrar en una disciplina, en un área determinada, donde tenemos un producto un poco más evaluable que además lo podamos referir a necesidades y posibilidades nacionales de corto, de mediano y de largo alcance.

Por lo tanto, si el informe que presentó el Dr. Villanueva puede ser calificado de teórico y general o abstracto y general, sin que ninguno de esos tres adjetivos sean peyorativos, sino descriptivos, lo que yo voy a proponer ahora es exactamente la antítesis de eso: es un análisis muy crudo, muy descarnado, muy sobre elementos primarios de la metalurgia. Y lo hacemos un poco de intento, porque así podemos comenzar a ver si ciertas ideas generales se pueden aplicar al análisis de situaciones particulares.

Conviene que diga algunas cosas para beneficio de las personas que no están familiarizadas con la industria metalúrgica. Algunos datos referentes a esta industria, en el contexto de la economía Argentina. Las que voy a decir son muy breves, y fáciles de recordar, pero justifican un poco que si hacemos un esfuerzo en la dirección que he dicho sobre metalurgia, tendrá alguna significación social y económica.

Si evaluamos la importancia de la industria metalúrgica en términos del producto bruto nacional, a la industria metalúrgica le corresponde el 10% del producto bruto, según los datos de 1963. El número de establecimientos de la industria metalúrgica, referido al número total de establecimientos de la industria general, es del 27%; el número de obreros empleados en la industria metalúrgica es del 32%, respecto al total de obreros empleados en la industria manufacturera general.

Estos tres parámetros, estos tres datos, dan idea de que hacer un esfuer-
zo en el sector de la metalurgia es importante no solamente porque sea nuestro
oficio, sino que además tendrá una significación económica social importante. Se
podría aproximar el problema de una evaluación de las prioridades en la investiga_
ción metalúrgica, sobre bases del siguiente tipo:

Se podrían proponer influencias de corto, mediano y largo alcance en la
economía nacional. Para dar un ejemplo: si tomamos un problema de
corto alcance podríamos tratar de evaluar en él el riesgo que incurriría
mos en investigar ese problema y los beneficios que obtendría la socie-
dad en términos sociales y económicos.

Hago hincapié sobre esto de la sociedad y no de un establecimiento o una in_
dustria particular, porque entiendo que no cabe discusión alguna que en países de
la estructura nuestra, países en desarrollo, no cabe ninguna duda deberá haber or_
ganismos de planificación que fijarán los objetivos sociales, no los objetivos indi-
viduales de determinado sector. Y digo que importa decir esto en términos socia_
les, porque es muy frecuente encontrarse con casos como este...:

Una persona viene y le dice a uno: Ud. qué investiga?
Y uno le contesta: un tema cualquiera -digamos dislocaciones- por decir
una cosa muy abstrusa...
Qué lástima! Uds. tendrían que investigar cosas concretas.
Entonces uno dice: Qué son cosas concretas?
Cosas concretas son los clips, como éste que tengo en la mano. Fíjese que
los que yo fabrico se rompen.
Uno le contesta: Qué lástima que se le rompan, trate de que no se le rom-
pan... (puede ser una respuesta).
Entonces el señor irá muy disgustado y dirá: En lugar de estudiar disloca-
ciones, debería estudiar cosas concretas, como los clips.

Claro, son cosas concretas para él, que mide los términos de su problema,
de su realidad de hoy a las 8 de la mañana, porque a las 10 quizás ya no fabrica más
clips. Si uno pudiera evaluar el estudio de dislocaciones en términos sociales, a lo
mejor es mucho más importante que los clips de aquél señor.

Un ejemplo posible en el caso particular de la Argentina podría ser el hierro
silicio para transformadores. En este caso nadie viene a golpear la puerta para ha_
cer preguntas científico-técnicas, porque el señor que importa el hierro silicio pa_
ra los transformadores y los construye, no tiene ningún problema de ese tipo. Su
negocio no es el hierro silicio; su negocio son los transformadores. Si él dispone
de hierro silicio en el mercado internacional y a lo mejor hace buenos negocios con
cosas laterales al hierro silicio, no tiene una preocupación latente. La tendrá el día
que se cierre la importación, el día que sobreve- a una guerra, o el día que exis-
tan mecanismos de presión. En ese momento el problema se transforma para él
en un algo concreto. Entonces el diagnóstico que debemos hacer debe conducirnos
a determinar cuáles son los problemas concretos en términos sociales.

Eso nos va a decir cuáles son los problemas concretos para hoy o para ma ñana. Esos problemas concretos, en términos sociales, no están relacionados a un individuo o a una preocupación individual solamente. Debieran estar relaciona dos a un análisis en amplitud y en profundidad. Los países no han hecho esto mu chas veces. Hay muchos ejemplos de que en los países, como estructuras socia les, no ha habido el incentivo directo del beneficio económico a que se refería el Dr. Villanueva anteriormente.

No es cierto que individualmente uno tenga presente esa necesidad social. En una economía de mercado lo que uno tiene presente son sus beneficios y 'este es su objetivo fundamental; para eso está. Entonces, cuando decimos analizar prioridades de investigación en términos sociales y no individuales, determina- ción de riesgos de investigación en términos sociales y no individuales, y enume ración en forma de lista o nómina de los problemas concretos de la metalurgia en un país, nos volvemos a referir a términos sociales.

Entonces, en los problemas de corto alcance una primera aproximación muy grosera, insisto que muy grosera, pero es una hipótesis de trabajo, sería analizar la sustitución de productos metalúrgicos por su influencia directa en la balanza de pagos. Esto que se hace cuando hay una emergencia nacional, una gue rra, un bloqueo, en lugar de hacerlo por una emergencia nacional podríamos ha cerlo con plena conciencia. Analizamos la lista de productos metalúrgicos que im porta el país y observamos su incidencia sobre la balanza de pagos. Medimos de esa manera su costo social, y esbozamos inmediatamente una primera lista, por así decir, de importancia. Esta lista no basta.

Aquí estaría la lista en relación con los términos de la balanza de pagos. No basta esta lista si no ponemos al lado otra lista que diga qué es lo que nos im pide elaborar, manufacturar estos productos que aquí estamos importando. El impedimento no son sólo dificultades tecnológicas o científicas; pueden ser conve niencias nacionales, políticas, de todo tipo. El organismo de planificación tam- bién deberá evaluar esto y darle algún tipo de prioridad; deberá analizar esas causas.

Por último tendríamos que hacer una tercera tabla y evaluar si los impedi mentos que nos impiden elaborar son de naturaleza tecnológica, o bien el producto está protegido por una red de patentes, por así decirlo, que impiden entrar a nos- otros en su manufactura. Son productos cuyas inversiones de capital exceden posi bilidades nacionales? Este análisis tiene que ver con el estado del producto en el mercado mundial; es decir, como son las reglas del arte de elaborac   de tecno logía y de ciencia, que están subyacentes en el producto en cuestión.

Con estas tres listas uno puede comenzar a hacer una primera secuencia de prioridades. Por supuesto por debajo de todas están las posibilidades existentes en el país, en materia de investigación. Si el país no tiene investigación toda esta lista -por supuesto - es ridícula.

Estoy partiendo de la base de que hemos aprendido la lección No. 0. Un país debe tener un estudio de investigación determinado. Esa lección la aprendimos hace bastante tiempo. Aunque no la hayamos aprendido del todo, aprendimos lo más importante. Entonces, esta primera aproximación de corto alcance (digo "de corto" porque solamente se ha tenido en cuenta un aspecto del problema económico, que es el impacto en su balanza de pagos), puede conducir por ejemplo, en el caso de la economía Argentina, a algunas cosas interesantes: la Argentina importa normalmente 20 millones de dólares aproximadamente en hojalata para envases de productos alimenticios. Ha sido una importación tradicional argentina, por supuesto. Estos 20 millones de dólares es una parte importante de nuestra importación anual, por cuanto importamos en el orden de los mil millones de dólares de productos totales, de manera que 20 millones de dólares no es una cifra ridícula o pequeña.

Qué importancia tendría una investigación que analizara aspectos tales como los siguientes: Por qué hojalata en tales envases o para tales productos? Por qué no otros productos? Por qué no aluminio? Por qué no plástico? Por qué no vidrios? Además: Por qué hojalata de tanto espesor, por qué hojalata de tal medida?

Y finalmente: Por qué no disminuir no solamente el espesor de la chapa sino el espesor del recubrimiento mismo, cuando este incide tanto en el producto final. Bueno, un desmenuzamiento de este tipo, del proceso, (estoy tomando un ejemplo relativamente ficticio, excepto los 20 millones de dólares), pero un desmenuzamiento de este problema tiene sentido por una razón muy importante: porque la tecnología de la hojalata es una tecnología vieja en el mundo. Existen numerosos sustitutos y sucedáneos que han sido desarrollados en otros países y que no han sido aplicados a sus economías respectivas, porque las inversiones de capital que están detrás de la industria de la hojalata, obstruyen esa aplicación. Por lo tanto, en el mercado internacional hay conocimiento en hojalata disponible, que podría ser transferido a la realidad nacional, re-analizado en términos del problema específico, y aplicado, si así fuere conveniente.

Pero hay algo más todavía: ése es un proceso dinámico, y así hemos visto hoy sorpresas mucho mayores que las de la hojalata, cuando hemos visto en las conferencias los otros días, la importancia de la fibra de vidrio en una cantidad de aplicaciones tradicionalmente metalúrgicas. En este terreno particular, el campo de posibilidades de creación original en términos de los productos nacionales o de los recursos nacionales- está muy abierto. Tendría sentido financiar, apoyar financieramente, investigaciones en este territorio. Y uno podría llegar en un segundo análisis a una valuación de riesgo, en la medida que uno dijera: si importamos 20 millones de dólares anuales de hojalata y un desplazamiento en su uso por otras cosas, puede reducir este costo social en dos millones de dólares, podemos saber cuánto valdría -en términos sociales- una investigación en hojalata.

Podríamos así arriesgar 2 millones de dólares, por cuanto si los perdiésemos sería una pérdida medida y en relación con una probable ganancia importante.

Entonces se podría hacer eso a través de un mecanismo crediticio adecuado, a través de un mecanismo de seguro o a través de los mecanismos de costo social que tiene toda economía.

Otro caso parecido al de la hojalata, con algunas variantes, es el de hierro silicio para transformadores. El país importa anualmente el orden de 10.000 tons. de chapa de hierro silicio. Hierro silicio para transformadores es una necesidad en todos los países, de cualquier parte del mundo, que comiencen cualquier proceso de industrialización, particularmente de electrificación. Una fábrica de transformadores es un buen símbolo de nivel tecnológico de un país. El hierro silicio es un material desarrollado y perfeccionado sobre todo en los últimos años por algunas firmas -particularmente americanas- que han protegido además ese desarrollo con una red de patentes tan cerrada que las firmas inglesas, en el mercado de hierro silicio, están ahora embarcadas en una investigación de manera tal de reemplazar el silicio en el hierro silicio, por cuanto de lo contrario no hay salida para esa trampa de patentes.

Acá tenemos un caso en el que no solamente hay un costo social sino un costo político. Por cuanto en la medida en que sobre el hierro silicio (que es un material tan estratégico como el cobre o más) haya un conocimiento, una tecnología monopolizada de una determinada manera, dependiente de una determinada estructura, nosotros tendremos no solamente un cuello de botella económico, sino un cuello de botella técnico. Entonces uno debe preguntarse cuál es el estado del arte de hierro silicio.

Esta es la segunda tabla a la que me refería anteriormente; es muy importante porque, claro, si el estado del arte es tal que nuestras chances de hacer algo en hierro silicio son cero, o casi cero, entonces el costo será tan grande que no podremos tomarlas. Esto exige un análisis con bases tan sólidas en metalurgia para saber a que distancia, o que dificultades son las que hay que vencer, que solamente un sólido conocimiento básico metalúrgico en un equipo de investigación puede dar la valoración correcta de esto. Y si uno no es capaz de darla, pues entonces puede no solamente no resolver el problema, que eso puede ocurrir muchas veces, sino cometer un desatino comenzándolo a estudiar.

En el caso particular del hierro silicio, para terminar con él, mi opinión personal (y a lo mejor en la audiencia va a haber mucha gente que difiera conmigo, y estaré encantado de que así sea) es que el conocimiento que ha derivado de esa malla de patentes es un conocimiento alcanzable, si se poseen conocimientos básicos fundamentales y se sabe, por supuesto, el oficio de investigar. Si se lo ignora no tiene sentido.

Los ejemplos de largo alcance tienen que partir de un análisis distinto que los de corto alcance. Los de corto alcance son basados en análisis inmediato de cosas, como la balanza de pagos, etc. Los de largo alcance tienen que basarse en un análisis distinto, que consiste esencialmente no en la predicción del riesgo económico, sino en algo diferente, en la predicción del cambio tecnológico. Ha-

cia donde va a cambiar la tecnología metalúrgica en los próximos 15 años. Una evaluación acertada del cambio de la tecnología metalúrgica en una determinada dirección, constituiría para un país en desarrollo, la posibilidad de un salto gigantesco en su desarrollo técnico, por cuanto le daría la oportunidad de convertirse de comprador de royalties, de pagador de "know-how" en el estado de subdesarrollo, al estado inverso: de exportador de conocimiento, exportador de "know how". Y lo que es más importante: una predicción adecuada del cambio permitiría que el país no instale industrias o tecnologías que son obsoletas en el momento mismo en que el país está tomando la decisión.

Estados Unidos posee instituciones especializadas en el análisis de la predicción de cambios tecnológicos. Rusia, por supuesto, en su estructura económica, filosófica más que económica, tiene subyacente este tipo de análisis. La O. E. C. D. está emprendiendo este análisis para ramas concretas de las disciplinas técnicas. Los países de América Latina deberán hacerlo con mayor razón todavía.

En el caso concreto, en el caso específico de la metalurgia, la predicción de cambio se podrá hacer en función de un análisis acabado del estado del arte actual, de un análisis de la proyección de las investigaciones en curso.

El Dr. Steinberg dió un muy buen ejemplo de eso en un caso muy simple en el fondo pero muy interesante, de las visiones para la década del 60 de las propiedades para materiales destinados a los motores de cohetes: vidrio (en caso de ser fabricados en vidrio) titanio o acero. El programa MEP que expusieron ayer el Dr. Reed y el Dr. Promisel, no es otra cosa que la previsión del cambio tecnológico en acción, pagado con el presupuesto social del país, para determinar "de facto" cuáles van a ser aquellas direcciones de cambio más importantes. Lo menos que debemos hacer nosotros es estar muy vigilantes al programa que expusieron el Dr. Reed y el Dr. Promisel. Porque ellos no solamente están haciendo una predicción teórica, sino que están invirtiendo no se cuántos millones de dólares en producir la predicción a través de la investigación concreta.

Nada más.

OBJETIVOS DE UNA COLABORACION REGIONAL EN MATERIA DE INVESTIGACION TECNOLOGICA

por Jorge Sábato

De acuerdo al programa preparado para la Conferencia, la Secretaría de Organización dispuso que en la sesión de hoy se discutieran medios para continuar esta tarea que hemos comenzado ahora. La experiencia ha servido para que discutiésemos una cantidad de problemas y, más importante aún, para que nos conociésemos y encontrásemos la manera de seguir adelante.

Quiero recordarles a todos los presentes que esta reunión no ha sido otra cosa que la consecuencia de la reunión de Bogotá de enero de 1963 convocada por la OEA con el objeto de discutir la manera de llevar adelante una colaboración regional en materia de investigación tecnológica, y que Metalurgia fué una de las áreas discutidas en aquella conferencia y elegidas para que se celebrasen reuniones regionales en las cuales habría que encontrar la manera de llevar a cabo esa colaboración. Por lo tanto, el meeting en conjunto de toda la semana debe ser tenido como la preparación básica y el primer paso hacia un programa más ambicioso que naturalmente no se pretende estructurar ahora en detalle ni mucho menos, sino dar un pasito más adelante.

De esta reunión para adelante deberán ocurrir otras cosas, deberemos hacer otras cosas. No debe terminar naturalmente en una simple expresión de buenos deseos, sino que la Secretaría de Organización está animada del propósito de que así como realizamos esta conferencia, realicemos otras cosas.

En tal sentido voy a sugerir algunas de las cosas que podrían hacerse y el debate ilustrará sobre otras cosas más. Esta es una lista tentativa y de ninguna manera completa.

Yo quisiera, antes de empezar a enumerar esta lista, pedir que todos ustedes contribuyan con sus propias ideas y que en alguna medida nuestra discusión de hoy esté realizada bajo el lema siguiente: no pretendamos la perfectabilidad, sino consigamos formas de hacer.

Hay una expresión inglesa que todos ustedes creo que conocen y es "wishfull thinking" (buenos deseos) y muchas veces en el pasado esto ha sido bastante tradicional en las asambleas o reuniones latinoamericanas donde se levantan las copas

y se brinda por la felicidad de todos, el amor que todos nos tenemos y la herencia hispánica común, un gran destino, pero cuando nos volvemos a casa nos olvidamos de que eso hay que implementarlo con acción. Es decir, no sirve para nada y creo que ha sido el pecado nuestro desde que América Latina hizo la gran hazaña de liberarse de España, que fué una obra común. Desde entonces a la fecha parece que hemos padecido de una especie de espejismo literario que nos conduce, como digo, a tener expresiones de muy buenos deseos y muy poca capacidad de acción.

La secretaría está inspirada en el propósito exactamente opuesto: que se realicen determinadas cosas, no las mejores, no las más perfectas, no todas, no de manera global y para siempre, sino de a pasos, como se construyen todas las cosas desde la familia hasta los países.

He aquí algunas de esas ideas:

1. <u>Entrenamiento del personal</u>

La revisión de lo que está ocurriendo en los distintos institutos muestra claramente que la necesidad de personal calificado es seria y que va a ser mucho más seria en los próximos años.

El entrenamiento de personal puede consistir en muchos tipos de cosas. Puede haber cursos regionales abiertos a todos los países, puede haber cursos de un área que por razones de comodidad o de transporte, por ejemplo digamos de Chile-Uruguay-Argentina, puede ser Chile-Perú-Colombia, tampoco tienen por que ser todos, pueden ser los que más convenga, los cursos pueden ser de naturaleza general si hay áreas de debilidad o pueden ser de temas muy específicos. Algunos de esos cursos regionales han existido ya y existen, podría citar el curso que el Departamento de Metalurgia de la Comisión realizó en el 62, llamado "primer curso panamericano" que contó con becarios de nueve países de latino américa. Hay otro curso parecido programado para el año 1965, que va a comenzar el 15 de marzo, de una duración de 10 meses. En estos cursos, tanto en el anterior como en este, como Uds. saben se dá mucho énfasis a dar una preparación muy sólida en ciertos aspectos de la metalurgia y se descuidan otros porque no se pretende abarcar todos.

Ese curso en alguna medida puede ser una buena chance para que ciertos institutos envíen becarios. Cursos que han existido a nivel interno como los cursos de la A. B. M. (Asociación Brasilera de Metales) que se organizan anualmente son extensos, muy conocidos y ha dado origen uno de ellos a la publicación del Dr. Correa Da Silva que creo todos conocemos aquí, podrían ser una posibilidad de que los Institutos se pusieran en contacto con la Asociación Brasilera o solicitaran la posibilidad de enviar técnicos y becarios a sus cursos, que se conociera con suficiente anticipación cuando van a ser, que temas, quiénes van a venir, etc., y habrá otras posibilidades que Uds. seguramente van a exponer.

El otro problema en materia de entrenamiento de personal, además de los cursos de este tipo, sería el problema de entrenamiento de investigadores en el sentido más general de la palabra, sin restringirlo de ninguna manera a la investi gación llamada básica sino a la investigación metalúrgica en los aspectos que cada país necesita más, y en ese sentido todos más o menos ahora tenemos una idea de lo que está ocurriendo en distintos lugares y dónde sería conveniente enviar gente de un Instituto al otro por períodos que pueden ser cortos, largos, medianos, de acuerdo a lo que uno desee.

Hay un último punto en esto de entrenamiento de personal, es el que se re fiere a entrenamiento de técnicos, de personal de operación. Esto se va a consti tuir cada vez más en el cuello de botella de las Instituciones que lleguen a trabajar en estado de régimen. Cuando una Institución comienza a operar no se nota demasiado la necesidad de contar con técnicos de operación debidamente entrena dos. Cuando la Institución va a pasar a estado de régimen ése es uno de los cue llos de botella más fuerte, al extremo de que está agravado por el hecho de que así como existen alguna centena de posibilidades de beca de los organismos más raros, diversos y generales del mundo para preparar personal superior es decir PHD o ingenieros graduados o cosas por el estilo, es muy difícil, aparentemente, encontrar recursos o incluso lugares para el entrenamiento de técnicos.

Creo que en el entrenamiento de "technicians", si no se adopta una políti ca desde ahora, nos va a dar dolores de cabeza dentro de 5 años como ya les da, por ejemplo, a los físicos. En latinoamérica se ha entrenado mucha gente en física, se dispone de excelentes laboratorios pero en este momento hay una escasez tan notoria de "technicians" capacitados, que es en verdad un ejército con genera les y sin soldados. Llamo la atención para que no nos ocurra lo mismo a nosotros.

2.   Utilización común, bilateral, o regional, de expertos
        extranjeros.

Recibimos de todos los países, corrientemente, metalurgistas de prestigio, que son caros, particularmente son caros de trasladar; una vez que han llegado a la Argentina muy poco costaría que hicieran una estada en el Uruguay o una estada en Chile o una estada en Sao Paulo, si esto se organizara con cuidado. Es decir, de obtener un poco más de beneficio no solamente de la capacidad técnica del hom bre, sino también de sus experiencias, de su tradición, etc.

Esta política, nosotros, desde la Comisión, la hemos seguido muy concien temente particularmente con los Institutos de Chile, Santiago, de Sao Paulo, que dirige el Dr. Correa da Silva, y también con el grupo de Córdoba. No siempre, pero generalmente la gente que invitamos nosotros, tratamos de que esté algunos días en Sao Paulo, otros días en Santiago y otros en Córdoba. Esto lo vamos a seguir haciendo, por supuesto, así de manera informal, no hay porqué firmar do cumentos para eso, basta con escribir unas líneas o hablar por teléfono, pero se ría bueno escuchar otras ideas, conocer por ejemplo quién es la gente que va a

venir en el año 1965 al área. Nosotros vamos a traer el año que viene aproxima-
damente 10 metalurgistas, algunos de renombre tan grande como Bruce Chalmers,
de Harvard, o Guinier, de Francia, o Dorn, de California, etc., pero sería muy
bueno tener una lista "a priori" que permitiera entonces que las demás institucio
nes expresaran su interés en una determinada persona. Creo que esto sería sim
ple de arreglar.

3.   Intercambio de personal "senior" de las instituciones

Creo que debiéramos encontrar mecanismos que hicieran posible que una
persona de nuestro laboratorio a nivel "senior" esté tres meses en un Instituto de
Chile, o de Colombia, o de Perú, con el objeto de realizar un trabajo concreto.
Eso lo va a llevar a un conocimiento más directo de lo que ocurre allí, particular
mente al nivel de operación.

4.   Temas concretos de investigación cooperativa

Habrá temas que puedan interesar a varios institutos. Yo he visto, por
ejemplo, en esta reunión que es la preocupación de varios Institutos, el problema
de arena de fundición. Un tema viejo, que a todos nos ha preocupado; en la Ar-
gentina se trabajó mucho en esto, hay una buena experiencia pero sería muy inte
resante probablemente, que dos o tres institutos del área tomaran el tema de are
nas de fundición e hicieran un grupo de trabajo de operación concreto con un co-
ordinador, pero un coordinador en algún lugar que convenga más y se haga un es
tudio sistemático.

La experiencia que está haciendo Chile, la que se ha hecho en la Argentina,
la que se ha hecho en el IPT, la que está haciendo el Uruguay. Sería de tanta ayuda
conocer, por ejemplo, nuestras materias primas, normalizar métodos, tratar de
diseñar métodos propios. Por ejemplo, que el trabajo del Ing. Lo Ré tenía una
idea central importante: un dilatómetro vale 15 mil dólares. Si el Ing. Lo Ré con
su aparatito lo ha resuelto mejor o peor que con el dilatómetro, esto no me impor
ta tanto, lo que importa es la inspiración que tuvo el Ing. Lo Ré.

Es muy común cuando no se tiene experiencia en investigación, comprar
aparatos por catálogo y creer además que los aparatos funcionan más o menos so
los. Alguien me dijo una vez que la imagen que en los países subdesarrollados se
tiene de la investigación, es que la investigación consiste en comprar un aparato
grande con muchos botones y uno aprieta los botones y después salen las respuestas.
Y si uno le une una computadora, se puede ir a su casa porque sale tabulado y casi
impreso para la revista correspondiente.

Bueno, todo esto lo sabemos bien o simplemente lo cuento a título de que
al tomar temas como el de arenas de fundición, donde hay un interés muy directo,
los encaremos con criterio original.

Se pueden sugerir otros temas de interés también multilateral. Por ejem
plo nosotros tenemos interés en electrodos para soldadura a punto para máquinas
de soldar, creemos que es un tema que tiene interés para muchos otros más que
nosotros, porque es un elemento que hay que usarlo y se va a usar cada vez más,
donde por otra parte, la competencia, el know-how del exterior no es demasiado
grande, digamos demasiado diferente, no estamos a distancias siderales del cono
cimiento. En el caso de electrodos aquí ha habido dos trabajos curiosamente so-
bre el mismo tema sin haber un acuerdo previo ni siquiera conocer el uno que lo
iba a presentar el otro, que es el trabajo de Sao Paulo sobre electrodos y el nues
tro sobre electrodos, lo que prueba que hay un problema común; no por casuali-
dad nos hemos ocupado los dos de lo mismo.

5.   Para la financiación de los trabajos

Para la financiación de los trabajos que queremos realizar nosotros, en
conjunto o individualmente, se dispone en los organismos internacionales general
mente, de una cierta cantidad de fondos con destino específico, como adiestra-
miento por ejemplo. Eso es necesario y debe ser utilizado. Pero yo creo que
habría que hacer alguna presión orgánica sobre ciertos organismos en particular,
para que además de entrenamiento destinen fondos para financiar trabajos de in-
vestigación y desarrollo.

Hay muy poca disponibilidad de lo que se llama "operating funds", fondos
de operación. Es muy curioso ver que uno puede conseguir bastante dinero para
' capital funds", pero esa es una trampa en la cual todos debiéramos tener mucho
cuidado, porque hay que hacer el cálculo de cuánto se necesita de "operating funds"
para cada dólar de "capital funds".

Obtener un préstamo de un millón de dólares para equipos y para expertos,
supone un presupuesto de funcionamiento de 100 a 150.000 dólares anuales. De
modo que antes de caer en la tentación de una máquina grande o de una instalación
cara, analicemos muy cuidadosamente dónde van a estar los "operating funds",
porque si no encontramos los "operating funds" ese peso del millón de dólares
nos puede hundir, de esto hay ejemplos en toda América Latina de institutos con
hermosos edificios y muy hermosos aparatos vacíos de toda actividad porque al-
guien se olvidó que los aparatos funcionan con gente y que hacen falta los cabl   i
tos, las termocuplas, etc.

6.   El problema de la evaluación de recursos humanos en
      metalurgia

El problema de la evaluación de recursos humanos en metalurgia en una proyec
ción al 70-80 de nuestras necesidades. Creo que podríamos pedir estudios un poco
específicos; proyección de recursos humanos y niveles de recursos humanos que
va a demandar no la metalurgia en general, sino nuestra actividad en metalurgia.

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This publication (2 volumes) contains all the works presented at the First Latin American Conference on Process Metallurgy and Metal Working, held in Buenos Aires, during August 18-23, 1964. It was organized by the Department of Metallurgy of the Argentine Atomic Energy Commission, with the co-sponsorship of the Department of Scientific Affairs of the Organization of American States, the Instituto Nacional de Tecnologia Industrial (INTI) (Argentina), and the United States Air Force Office of Scientific Research, being its aim to analyze the possibility of co-operation in the field of metallurgy research -among Latin American Institutions- in order to develop a strategy elaborated from the study of the present state of Process Metallurgy in developed countries, the programs being held in Latin America and the Institutions' own needs.

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	Aluminum						
	Aluminum Alloys						
	Steels						